Review of a 1-D Heat Budget Model of the Columbia River System

Oregon, Washington, and Idaho

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Executive Summary

The U.S. Environmental Protection Agency's (EPA) rationale for their one-dimensional thermal model of the lower Snake and Columbia Rivers is to enforce the Clean Water Act. Although EPA identifies various sources of the problem, the model focuses on simulating how many days the river at each dam exceeds the existing standard of 20ºC. By simulating thermal behavior of a restored river channel (no dams), EPA demonstrates a reduction of 0 to 12 percent of the days violations would occur depending on location. In the mid-Columbia reach, there are no violations without reservoirs, but very few with reservoirs, and these are over an 18ºC. standard. Lower Snake reservoirs violate the standard 15 to 18 percent, but a restored channel ameliorates only up to 4 percent of the violation. This is because the input temperatures are already in violation of the standard when they enter the modeled reaches. The lower Columbia reservoirs also exceed the standard about 15 percent of the time. According to the model, channel restoration would reduce lower Columbia violations to less than 5 percent of the time.

Although EPA does not acknowledge it, upstream water is often the strongest predictor of downstream temperature. The warm water from the input source in the Snake is often in violation of the standard before it is modeled in the lower Snake reach. The large mass of warm Snake River water pushes the marginally "legal" water in the lower Columbia over the edge creating violations downstream but their root cause is upstream. Given the huge mass of water in this system, it should not be surprising that temperature is relatively inelastic to cooling by low volume tributary inputs or even Draconian measures of removing huge reservoirs.

There are many questionable aspects to the EPA model but the most troubling is their data. By EPA's own admission, "The quality, bias and variability of these data vary considerably from site to site." and "The variation in the data quality makes the task of quantifying the measurement bias and error a difficult one." Model calibration, or its ability to "predict" is a function of its ability to minimize error variance from a variety of sources including instrument bias, missing data, extrapolation of unknown or missing data and variables, recording errors, and assumptions about the interaction of the variables. EPA is unable to account for the error variance from most of these sources and instead uses various mathematical techniques to improve the data. The model also has problems. Because the model lacks good data, it simplifies or artificially constructs many of the thermal drivers with surrogates unsuited for the job. Three examples: EPA has only four weather stations with complete contemporaneous data to assess meteorological conditions in the entire basin. All other data are simulated or sewn together from different locations or time frames using mathematical assumptions about their relation to river temperature. Second, EPA assumes that all reservoirs or their reaches are likely to affect temperature similarly. Our analysis shows that the variety of the depths, lengths, widths, and gradients of the "reservoirs" would each produce different surface to volume ratios and thermal behavior if removed. Many of the reservoirs stratify and there are better models to predict thermal behavior. Third, key drivers of river temperature include longwave radiation and input temperature, yet nowhere is there any assessment or calibration of radiation.

Salmon health and risk from temperature is given as a primary reason for concern that temperatures exceed 20°C. Salmon have adapted to dealing with high temperature; they avoid it if possible. The homogeneous model of EPA suggests salmon cannot avoid thermal violations. However, this is only an assumption about the river, which both we and the salmon know is not true. The EPA violation criterion creates an artifact that both exaggerates the thermal problem and minimizes credit to mitigate for it in incremental steps. By selecting days of violation above 20°C, EPA counts 0.1°C excursion above 20°C as serious as a 3°C violation. Likewise, any mitigation that reduces the temperature from 23°C to 20.1°C is assessed as zero benefit to the salmon and a violation of code. Neither situation reflects reality for fish or people. If we are going to use 0.1°C as a measuring stick of violation, we need a tool that has lower measurement bias than 1.5 to 2.0°C as acknowledged on page 34 of EPA's report. We should not assume that the temperature in one turbine, even if accurate, truly reflects temperatures throughout the river.

Section 1 - Introduction

1.1 Rationale for the Model

EPA's rationale for preparation of a 1-D Heat Budget Model of the Columbia River System is given in the broadest terms of enforcing the Clean Water Act. The Introduction says that waters of the Columbia and Snake from Anatone in the Snake and Grand Coulee in the Columbia to Astoria at the sea

> "…do not meet water quality standards during all or part of the year. Impairments are identified as…construction of impoundments…which increase the time waters …are exposed to high summer temperatures, …modifications to the natural river system to generate electricity …irrigation water for farmland… facilitate navigation…agriculture… silviculture…and pulp and paper manufacturing facilities that discharge thermal energy."
> "Water temperature is one of the most frequently occurring constituents on Oregon's and Washington's list of water quality limited segments on the Columbia and Snake Rivers" (p. 2, para. 1).

The majority of the 60-page document however is a description of a one-dimensional model of the thermal behavior of these downstream sections of the Columbia and Snake Rivers and the results and conclusions from that model. The framework for the model has three scenarios: the existing system; the system without any of the dams; and the system controlling the thermal input from 12 tributaries. Regarding the tributaries, EPA concludes (p. 47, para. 2) that: "The impact of these sources on the thermal energy budget of the mainstem Columbia is, therefore, small." Thus Scenario No. 3, controlling the tributaries, is not useful for thermal regulation of the mainstem according to EPA's model.

1.2 Mathematical Goals of the Model

The EPA developed a mathematical model in 2001 to predict the daily average water temperatures in specified segments along the Columbia and Snake Rivers. The water temperature is an average across the width and depth of the river. This model is based on the energy budget method and uses numerical techniques to simplify the characterization of model uncertainty. This energy budget method accounts for the heat exchange with the atmosphere and the input of advected thermal energy from major tributaries and point sources. A report titled "Application of a 1-D Heat Budget Model to the Columbia River System, dated March 7, 2001" (EPA, 2001) discusses the details of the model developments, methodologies, assumptions, limitations, databases, inputs, and outputs.

The objective of the model study is to determine the relative impacts of the operation of dams and reservoirs on the thermal energy budget. The specific objectives are to:

- Estimate the magnitude and frequency with which the daily average water tempertures in the Columbia and Snake Rivers will exceed the reference 20°C (68°F) under existing conditions of river management and a representative record of river hydrology and meteorology.

- Estimate the magnitude and frequency with which the daily average water temperatures in the Columbia and Snake Rivers will exceed the referenced 20°C with no dams in place below the Grand Coulee Dam on the Columbia River and no dams in place below Lewiston, Idaho, on the Snake River.

- Estimate the magnitude and frequency with which the daily average water temperatures in the Columbia and Snake Rivers will exceed the reference 20°C under existing conditions of river management and with major tributaries and point sources constrained to temperatures less than 16°C (60.8°F).

- Characterize the uncertainty of these estimates for the purpose of ultimately assessing the risk associated with potential management decisions in the Columbia and Snake Rivers.

1.3 Context of the Model: Tributaries versus Mainstem

If we look no further, the reader should understand EPA's perspective and framework of this model. If we were to simply advect (mix) cold tributaries with a warm mainstem, there would be some cooling and the average temperature of the mainstem would decrease, even if slightly. However, if it does not cool the river below 20°C, then according to EPA's framework, it is as if no thermal mitigation from such tributaries has occurred at all. This is because EPA's criteria of effectiveness are the number of days the temperature of the river averages above 20°C. Thus if we were to somehow cool a 23°C river by 2.9°C to 20.1°C, no improvement would be measured by EPA's model criteria. However, by EPA's own admission (p. 9, para. 2), the risk to salmon increases as the water warms above 20°C. Yet, the model implies no difference between 20.1°C water and 23°C water. This model implies that we should abandon improving thermal TMDL's in our tributaries, a conclusion most would be surprised as coming from EPA.

The second perspective we obtain from EPA's framework is that the model is not addressing farmland, or agriculture, or silviculture, or navigation, or pulp and paper, or dozens of potential impacts to a thermal TMDL as it alludes might be important on pages 1 and 2.

Instead, EPA's framework of the model "with and without" dams implies only a single solution: that temperature violations might be reduced if the dam owners lowered or removed some or all of the federal reservoirs downstream of Brownlee Reservoir and Lake Roosevelt. If this is not the case, nowhere in the document do we find other suggestions on how to improve the thermal condition in the mainstem. Before we accept this or any other mitigation, tacit or otherwise, it will be important to review the basis for this conclusion. Our review of the EPA publication and model will examine the following aspects of the above:

- The premise for the investigation and its legitimacy
- The model EPA uses to simulate the thermal regime without dams
- The data EPA uses in the model
- The significance EPA places on the magnitude of the thermal loading
- The biological premises of thermal conditions with and without dams
- Improvements EPA made or did not make to the 2000 draft of the model

1.4 Thermal Criteria of the EPA Model

The thermal criteria EPA uses is that instantaneous temperature in the Columbia River should never exceed 20 ºC (68 ºF) or 18ºC (64.4ºF) upstream of Priest Rapids Dam to Grand Coulee Dam. The constraint of 16ºC (60.8ºF) on maximum temperatures in the tributaries is based on the State of Washington's water temperature criterion for tributaries classified as Class A (excellent). The use of this constraint does not imply that the tributaries have attained this criterion or would do so in the future. It should be viewed only as a model reference to evaluate the relative thermal impact of the tributaries of the mainstems of the Columbia and Snake Rivers. Washington and Oregon Administrative Codes promulgate temperatures should not exceed these levels due to human activities. The biological basis for the criterion is that "adult salmon are at risk when water temperatures are warmer." Risk is not defined except for several quotes from the literature: "…20ºC is the water temperature where the zone of lower resistance starts for immigrating adult salmon and steelhead (p. 9, para. 2), and "…at 21.1ºC (70ºF) salmon are in a lethal range where the time it takes to kill the fish declines rapidly." EPA does not say that 20.1º or 21º or 22ºC is lethal to salmon or under what conditions it would be lethal, or how much exposure is required to these temperatures. It does say that the higher the temperature, the more the risk. However, the EPA model treats violations of 0.1ºC identical to violations of 3ºC even though, by their own evaluation, the risk of adverse impact to salmon increases with the increase of temperature, i.e., risk of 20.1ºC is not equal to risk of 23.0ºC. Additionally, since the model computes an average or simulated average temperature for a 24-hour period, it is not comparable to the standard of an instantaneous reading.

1.5 Assumptions and Data

An important assumption EPA makes is that the temperature of the river is assumed to be temporally and spatially uniform over a 24-hour period, based on a single reading at a point location. These data and simulated data come mostly from a single location in one turbine passage at each dam. And, if data have gaps of more than 24 hours, the temperatures are assumed constant until a different reading is attained. Further, the temperatures were recorded by different technicians reading mercury thermometer levels at different locations from instruments that were (presumably) not calibrated to one another. These circumstances led EPA to admit, "The quality, bias and variability of these data vary considerably from site to site" and "The variation in the data quality makes the task of quantifying the measurement bias and error a difficult one." (p. 34, para. 3).

The hydrologists who assembled the database (McKenzie and Laenan, 1998) identified "stepping" as one of many data problems. Stepping is a result of "the frequency (i.e., infrequency) with which scroll case temperatures were measured and reported in the past." They reported bias and variability as high as 2°C. EPA suggests bias in the range of 0.0 to 1.5 in the recent (1990-present) data. However, EPA used data from 1975 to develop the model parameters (p. 42, para. 2). EPA also attempts to construct a meteorological model using meteorological data. Our review of that data suggests very poor correlation between the EPA simulated input data and actual independent measurement data from nearby U.S. Bureau of Reclamation (USBR) and other meteorological stations.

Following is a detailed review of the EPA 1-D Thermal Model itself.

Section 2 – 1-D Heat Budget Model

2.1 Model Boundaries

The system boundaries of the model include the reaches in the Columbia River from the tailwater of Grand Coulee Dam at river mile 596.6 to Bonneville Dam at river mile 145.5 and the reaches in the Snake River from its confluence with the Grande Ronde River at river mile 168.7 to its confluence with the Columbia River near Pasco, Washington, at river mile 0.0. There are ten dams downstream of Grand Coulee Dam in the Columbia River and four dams downstream of Lewiston, Idaho, in the Snake River.

Since it is necessary to simulate daily average water temperature, the lower limit on model time scale is set to equal to 1 day. The upper limit on the model time scale is set to equal the time period constrained by the hydrology and meteorology data available for the Columbia and Snake River system under existing management. The period of existing management is referred to the operation period for the Columbia and Snake River system after the completion of Lower Granite Dam in 1975. Therefore, the upper limit of the model time scale is 21 years, from 1975 to 1995.

The model length scale is determined by the availability of geometric data, spatial variability in the river geometry, and computational stability and accuracy. Since there are ample data to describe river geometry in both the Columbia and Snake Rivers, the primary factor in determining the model length scale is the need to achieve stable and accurate solutions. With the lower limit of model time scale set at 1 day, the model length scale is based on the travel distance for a parcel of water to traverse within a computational time segment such as 1 day. The travel distance is therefore dependent upon the river velocity. For the Columbia and Snake Rivers, the model length scale is on the order of 1 to 10 miles (EPA p. 25)

2.2 System Model

The EPA one-dimensional model is a thermal energy budget model used to simulate daily average water temperature in the Columbia and Snake Rivers. The model consists of a system model and an observation model. The system model is used to estimate the change in water temperature. The basic equation for the system model is:

$$\rho\, C_p A_x\ (\partial T / \partial t) + \rho\, C_p (\partial\, (QT) / \partial x) = w_x\, H_{net} + S_{adv} + w_T \qquad (1)$$

where

ρ = density of water

C_p = specific heat capacity of water

A_x = river cross-sectional area at distance x

T = true water temperature

Q = river flow rate

w_x = river width at distance x

H_{net} = heat flux at the air-water interface

S_{adv} = heat advected from tributaries and point sources

w_T = random water temperature force function

x = longitudinal distance along the river axis

t = time

Equation 1 is a state-space equation for water temperature in the Eulerian frame of reference. (It should be noted that the river discharge in the model is constant for any given hour throughout the entire river reach, unlike the operation of the real river, where local storage of water causes wide variations in the instantaneous river flow.) The solution technique used is a mixed Eulerian-LaGrangian model, which employs the concept of a reverse particle tracking mechanism to implement the LaGrangian step. A LaGrangian frame of reference moves with the water and the Eulerian concept employs a reference fixed in space with water flows.

It should be noted that the one-dimensional system model assumes no longitudinal dispersion. Therefore, Equation 1 can be simplified as:

$$\rho \, C_p A_x \ (dT / dt) = w_x H_{net} + S_{adv} + w_T \qquad (2)$$

In Equations 1 and 2, the heat exchange across the air-water interface, H_{net}, can be described as:

$$H_{net} = (H_s - H_{rs}) + (H_a - H_{ra}) \pm H_{evap} \pm H_{conv} - H_{back} \qquad (3)$$

where

H_{net} = net heat exchange across the air-water interface

H_s = shortwave solar radiation

H_{rs} = reflected shortwave solar radiation

H_a = longwave atmospheric radiation

H_{ra} = reflected atmospheric radiation

H_{evap} = evaporative heat flux

H_{conv} = conductive heat flux

H_{back} = blackbody radiation from water surface

The equations used to compute the shortwave radiation, longwave radiation, evaporative heat flux, conductive heat flux, and blackbody radiation are presented in equations 5 to 9 as shown in the EPA report (EPA, 2001).

2.3 Observation Model

The observation model is used to link the observed water temperature data to the system model. The observation model for the one-dimensional thermal budget model simulates the water temperature at the K^{th} time interval using the Kalman filter theory (Gelb, 1974). The Kalman filter is one method that can be used to estimate the change in water temperature based on the observations. The following equation describes the process:

$$Z_k = H_k T_k + V_k \qquad (4)$$

where:

Z_k = the measured value of water temperature

H_k = the measurement matrix

V_k = the measurement error

When the measurements are available, the state estimation methods combine the estimates from the system model (Equation 1 or 2) and the observation model (Equation 4) to obtain an optimal estimate of the system state. The Kalman filter (Gelb, 1974) gives an unbiased, minimum squared error estimate of the system state for the filtering and prediction problems when all parameters in Equation 1 or 2 and Equation 4 are known. For the filtering problem, the Kalman filter combines the state estimates from the system model and the observation model. The two estimates are combined using a weighting factor determined by the relative uncertainty of the system model as compared to the uncertainty of the measurement model. The details of this method are discussed in the EPA report (EPA, 2001).

2.4 Hydraulic Characteristics

The information required to obtain a solution to Equation 1 or 2 includes: a) river width,

b) river cross-sectional area, c) river velocity, and d) net heat exchange. The hydraulics of the unimpounded reaches of the river system are estimated from power equations relating mean velocity, cross-section area, and width (Leopold and Maddock, 1953). These relationships are expressed as:

$$U = A_u Q^{Bu} \tag{5}$$

$$A_x = A_a Q^{Ba} \tag{6}$$

$$W_x = A_w Q^{Bw} \tag{7}$$

where:

U = river velocity
A_x = river cross sectional area
Q = river flow
W_x =river width

The coefficients, A_u, B_u, A_a, B_a, B_u, A_w and B_w, are estimated by simulating river hydraulic conditions under various flow conditions. Based on the gradually varied flow method, the COE (COE, 1995) derived the values of the above coefficients for the unimpounded condition in the Columbia and Snake Rivers. For the impounded conditions, the water surface elevation, surface area, and volume were obtained from the cross sectional data presented in the Columbia River Thermal Effect Study (Yearsley, 1969), COE cross sectional data, and NOAA navigation charts.

2.5 Model Input Data

2.5.1 Water Temperature

River water temperature data for the Columbia and Snake Rivers are needed for the model so that the data set can be used to describe uncertainty in the observation model. Extensive water temperature data were compiled by McKenzie and Laenen (1998) for the main stem Columbia and Snake rivers. The data quality analysis performed by McKenzie and Laenan provides a basis for characterizing the uncertainty associated with the measurements. Temperature data for the tributaries were obtained from observations made by the Idaho Power Company, Washington State Department of Ecology, and the U.S. Geological Survey (USGS).

2.5.2 *River Geometry*

River geometry is needed to describe the hydraulic characteristics of the Columbia and Snake Rivers. The river hydraulics are described as a function of flow and time. The basic data are the water surface elevation at a sufficient number of cross sections so that the water depth and width and velocity can be described as a function of flow. The river geometry is prescribed for the impounded conditions with dam in-place and for the unimpounded condition with dam removed.

2.5.3 *Hydrology*

Flow data for the main stem Columbia and Snake Rivers and major tributaries are part of inputs to the model. These data were obtained from the records from the USGS. The estimated groundwater return flow were obtained from Hansen et al. (Hansen, 1994). The groundwater flow data are used to estimate the advected heat inputs to the tributaries and Columbia and Snake Rivers.

2.5.4 *Meteorology*

Meteorological data, including solar radiation, barometric pressure, cloud cover, wind speed, air temperature (dry-bulb), and relative humidity, are required to calculate the heat exchange at the air-water interface. These data were obtained from four Weather Service stations, which are referenced as the first order meteorological stations. These data were used to estimate heat budget parameters for the Columbia and Snake Rivers. The daily maximum and minimum air temperatures recorded in the Local Climatological Data Sets were included in the parameter estimation for the heat budget calculations. The AgriMet network maintained by the Bureau of Reclamation records the daily average for all necessary meteorological data except the cloud cover. The data from selected AgriMet and other stations in the network were also prescribed as part of the meteorological input files.

2.6 Model Parameter Estimation

The values of the parameters for the system model (Equation 1 or 2) and observation model (Equation 4) are determined so that best fit can be made between the predicted measurements and the observed measurements. It is generally based on the least square method. The parameters required to determine the travel times are derived from the analysis of the system hydraulics. The components shown in Equation 3 are the source terms. The parameter estimation process is implemented in three steps:

- Estimate the deterministic parameters such as components of heat budget, advected thermal input, and travel times.

- The estimated deterministic parameters are adjusted until the simulated results for the system model are approximately unbiased. The system model is unbiased if the mean of the innovation vector is small. The innovation vector is the difference between time-updated simulations from the system model and the actual measurements.

- Estimate the variance of the system model.

The parameters describing the hydraulic characteristics were estimated from Equations 5 to 7. The daily flow at any location in either the Columbia or Snake River was determined from the sum of the estimated groundwater return flow and the daily gaged flow in the mainstem and the tributary flow upstream of that location. The variables in the meteorological input files were either directly measured or simulated using correlations from other data that were often quite temporally or spatially remote (see data analysis section). These input variables were then used to quantify the heat flux terms shown in Equation 3. The daily water temperature, which is used as initial conditions on the tributaries to the Columbia and Snake Rivers, was not always available. Mohseni et al. (1998) developed a nonlinear model to synthesize water temperature in the river. For most tributaries, the parameters used in the method by Mohseni et al. were estimated based on 2 to 4 weeks of temperature data in the tributaries. The input temperature is one of the most critical components of estimating a downstream temperature. Thus, the absence of any absolute starting temperature that has little measurement error, much less any simulation error, is an important flaw or weak point in this model (again, see data analysis section).

2.7 Model Assumptions

Due to the size and spatial variation of the Columbia and Snake River system, several assumptions were incorporated in order to simplify the modeling process. The major assumptions include:

- The model is used to predict daily average water temperature. The estimated water temperature is not a real-time temperature. The water quality standards in Oregon and Washington are written in terms of real-time temperature.

- The input water temperature is characterized as an average across the width and depth of the river. In fact, it is measured at a singular point at most locations once per day. Such a framework does not acknowledge the fact, much less account for, dynamic lateral and vertical variations in river temperature.

- The model neglects the dispersion and the longitudinal turbulent diffusion.

- The modeled river hydraulics are based on gradually varied flow method, whereas the flow regime in the Columbia and Snake Rivers is actually an unsteady flow.

- The Kalman filter is used to estimate the parameters of a linear system model, whereas the state-space equation for the water temperature is a mixed Eulerian-LaGrangian equation.

- The Kalman filter is a linear predictor. This linear approach is used to predict non-linear estimates of change in water temperature.

- The observed water temperature recorded in the dissolved gas monitoring program is based on a temperature probe located in the forebay of each dam usually at a depth of 15 feet or greater below the water surface. This temperature does not reflect temperatures at the water surface.

- The meteorological data from four first order weather stations are the basis to estimate the heat budget for the entire Columbia and Snake Rivers system. These weather data are far from the river reaches they are meant to simulate. This approach does not consider the regional variations in weather and topography. Analysis of the input data shows correlations with actual data that are too weak to provide precise estimates of a deterministic model (see data review section).

- The water temperature stratification effects are ignored for all reservoirs in the Columbia and Snake rivers. This not only has enormous physical connotations to thermal behavior, it probably has important biological connotations if the primary driver to cool the river is salmon. In short, salmon may move to cooler sections of a heterogeneous environment. Thus the model lacks significant component of reality which is important to the purpose of the model.

Section 3 – Discussions of Model Application

3.1 Impoundment Effects

The three parameters required for obtaining the solution to Equation 1 or 2 include the surface area for heat flux, and the water depth and volume (cross sectional area) in each segment of the rivers. Therefore, the values of these parameters are computed for the impounded and unimpounded conditions so that the order of magnitude difference between two conditions can be used to determine their impact on the water temperature calculation.

Based on the hydraulic coefficients presented in Appendix C of the EPA report, the river depth, surface area, and volume for each segment of the Columbia and Snake rivers under the unimpounded conditions were computed. For the impounded conditions, the surface area and volume for each segment of the rivers were used to compute the river depth and width. Tables 3.1 and 3.2 present the results of the computed river depth, surface area, and volume for each segment of the rivers. The results in the tables represent the conditions with dam in place and dam removed.

For the unimpounded condition, the river depth and width are a function of the river flow. From Table 1-2 of the EPA report, the average flow downstream of the Ice Harbor Dam in the Snake River is 53,400 cfs and the average flow at the Dalles in the Columbia River is 191,000 cfs. Therefore, the referenced flow used to estimate the river depth and width under unimpounded condition were assumed at 60,000 and 200,000 cfs for the Snake and Columbia rivers, respectively. It should be noted that the flows at each segment of the rivers were different. The referenced flows were assumed to be constant between the upstream and downstream boundaries of the rivers. For the unimpounded condition, the river depth and width at upstream segments of the rivers should be less than those shown in the tables. However, this assumption provided an easy way to show the differences between the impounded and unimpounded conditions.

Figures 3.1, 3.2, and 3.3 show the river depth, surface area, and volume in the Snake River for the impounded and unimpounded conditions. Figures 3.7, 3.8 and 3.9 show the river depth, surface area, and volume in the Columbia River for the impounded and unimpounded conditions. The river mile of the midpoint in each segment is used to represent the location of each segment. Figures 3.4 and 3.10 show the percent of change in river depth, surface, and volume between the impounded and unimpounded conditions in the Snake and Columbia Rivers, respectively.

For the Snake River, the weighted averages of the river depth, surface area (x1000), and volume (x1000) for the segments in each reservoir under the impounded and unimpounded conditions are summarized as follows:

Dam	Dam In Place			Dam Removed		
	Depth (ft)	Surface Area (acre)	Volume (acre-feet)	Depth (ft)	Surface Area (acre)	Volume (acre-feet)
Lower Granite	55.4	590	32,750	12.5	303	3,209
Little Goose	53.2	724	40,534	10.2	416	4,088
Lower Monumental	60.3	611	38,194	11.6	366	4,103
Ice Harbor	46.8	722	33,005	13.9	410	4,449

For the Columbia River, the weighted averages of the river depth, surface area, and volume for the segments in each reservoir under the impounded and unimpounded conditions are summarized as follows:

Dam	Dam In Place			Dam Removed		
	Depth (ft)	Surface Area (acre)	Volume (acre-feet)	Depth (ft)	Surface Area (acre)	Volume (acre-feet)
Chief Joseph	104.9	930	79,983	20.6	953	18,653
Wells	21.8	1,592	34,262	21.5	804	17,902

	Depth (ft)	Surface Area (acre)	Volume (acre-feet)	Depth (ft)	Surface Area (acre)	Volume (acre-feet)
Rocky Reach	34.3	1,331	49,419	23.5	890	19,745
Rock Island	41.8	814	33,462	25.1	704	16,589
Wanapum	24.5	2,268	58,776	18.2	2,081	36,462
Priest Rapid	26.2	1,527	40,070	19.0	1,388	26,177
McNary	39.0	2,841	92,790	13.0	1,485	18,863
John Day	51.6	3,007	146,586	16.4	1,413	22,568
The Dalles	34.9	1,768	61,719	22.2	1,369	30,343
Bonneville	32.8	1,858	60,656	18.8	1,473	26,650

Impoundment in the Snake River increase the surface area 71 to 135 percent; whereas, the depth increases 310 to 504 percent, and volume increases even more to 711 to 1,037 percent.

For the Columbia River, the change due to the impoundment is not as sizeable as that estimated for the Snake River. The surface area only increases between 6 and 118 percent, the depth increases between 5 and 471 percent, and volume increases between 64 and 631 percent. The changes in depth, surface area, and volume are varied from dam to dam. The following dams have volume changes more than 150 percent: Chief Joseph, McNary, John

Day and Bonneville. The following dams have volume changes less than 150 percent: Wells, Rocky Reach, Rock Island, Wanapum, Priest Rapids, and The Dalles.

Within a water body, the degree of heating is a direct function of the ratio of the surface area to the volume of the water. For example, the surface area in the Chief Joseph Dam only increases by 6 percent with the impoundment, but the depth increases by 471 percent and the volume increases by 454 percent. With small increase in surface area, the heat exchange through the air-water interface would be about the same between the impounded and unimpounded conditions. However, with the significant increase in depth and volume, the water temperature rise would be less for the impounded condition than the one for the unimpounded condition. On the other hand, the depth in the Wells Dam only increases by 5 percent with the impoundment, but the surface area increases by 95 percent, and the volume increases by 101 percent. Consequently, the heat exchange through the air-water interface would be more, which would result in a water temperature rise for the impounded condition. Therefore, the impoundment does not necessarily imply that the water temperature would increase as compared to the unimpounded condition.

It should be noted that the detailed methods of estimating the flow in the Columbia and Snake rivers for the unimpounded condition are not discussed in the EPA report. The validity of the method used to estimate the river flow for the unimpounded condition would determine whether or not the synthesizing flow could be used to correctly predict the depth and volume in the river, which would directly affect the solution of water temperature change in Equation 1 or 2.

3.2 River Velocity

River velocity is used to determine the length scale of each segment of the rivers. The diffusion due to river turbulence is not simulated in the 1-D heat budget model. The water temperature rise (above ambient water temperature) predicted by the traditional hydrothermal far-field model for the advective thermal input into the river generally includes the effects due to the heat transfer at the air-water interface and the mixing due to river turbulence. The mixing due to river turbulence is a critical part of the dynamics that contribute to heat loss in rivers. River velocity can be used indirectly to reflect the turbulence in the river, i.e., the greater the velocity, the higher the river turbulence. Therefore, the velocity for the impounded and unimpounded conditions was estimated for each segment of the rivers in order to examine its role in the heat loss.

Figures 3.5 and 3.11 show the estimated velocities in the Snake and Columbia Rivers, respectively. The referenced flow of 60,000 and 200,000 cfs (as discussed in Section 3.1) was used to estimate river velocity in the Snake and Columbia Rivers, respectively. It can be seen that the impoundment in the Snake River would result in a velocity of less than

1.0 ft/second in the reservoir, whereas, velocity for the unimpounded condition would generally exceed 5.0 ft/second in the river channel. For the Columbia River, impoundment would result in a velocity around 4.0 ft/second for the upstream reservoirs and 2.0 ft/second for the downstream reservoirs. For the unimpounded condition, velocity would exceed 7.0 ft/second for the upstream reaches and 4.0 ft/second for the downstream reaches.

It should be noted that the above velocity is only an average value across the depth and width. Velocity in specific areas would be much faster than the average value, especially for the unimpounded condition. For example, velocity along the riverbank would be much slower than the average value, whereas, velocity in the center of the river channel would be much faster than the average value. River turbulence is a source for increasing heat loss in the river. Therefore, based on the magnitude of the estimated velocity for the unimpounded condition, the assumption of no river diffusion would ignore a major parameter in estimating heat loss in rivers.

The system model for the 1-D heat budget model is based on Equation 2. It neglects heat flux crossing river cross-sections. The second term in Equation 1 represents longitudinal heat flux. This implies that the continuity of heat flux in the river between the adjacent segments is not considered in the model. This creates another error in the heat exchange estimations for unimpounded conditions.

3.3 Reservoir Stratification

The vertical water temperature gradient is not considered in 1-D heat budget models. This assumption is probably applicable for unimpounded conditions. However, depending upon the reservoir depth, cross section area, and flow rate, reservoir stratification could exist in a deeper, more voluminous reservoir.

Experience with prototype reservoirs shows that there are three classes of reservoirs. Each class requires a different type of solution to determine its temperature distribution. These classes are: a) a deep reservoir that is characterized by horizontal isotherms, b) a weakly stratified reservoir that is characterized by isotherms along the longitudinal axis of the reservoir, and c) a completely mixed reservoir whose isotherms are vertical.

The single most important parameter determining the reservoir class is the densimetric Froude number, F, which can be written as:

$$F = ((L * Q) / (D * V)) * (\rho_o / (g * \beta)^{0.5} \qquad (8)$$

where:

L = reservoir length

Q = volumetric discharge through reservoir

D = mean reservoir depth

V = reservoir volume

ρ_o = reference density

β = average density gradient in reservoir

g = gravitation constant

The densimetric Froude number is the ratio of the initial force of the horizontal flow to the gravitational forces within the stratified impoundment. Therefore, it is a measure of how the horizontal flow can alter the internal density (thermal) structure of the reservoir from that of its gravitationally static-equilibrium state. For a deep reservoir (with a low enough longitudinal velocity), the densimetric Froude number would be very small, whereas for the completely mixed reservoir, the densimetric Froude number would be very large. The weakly stratified reservoir lies between these two extreme classes.

For the purpose of classifying reservoirs by their densimetric Froude number, β and ρ_o may be approximated as 10^{-3} kg m^{-4} and 1,000 kg m^{-3}, respectively. Equation 8 can be expressed as:

$$F = 320 * (L / D) * (Q / V) \qquad (9)$$

Therefore, the principal reservoir parameters determining a reservoir's classification are its length, depth, and discharge to volume ratio (Q/V). The values of length, depth, and volume of each reservoir on the Snake and Columbia Rivers were obtained from the EPA report (Appendix C-1 for the Snake River and Appendix C-2 for the Columbia River). The only unknown would be the discharge through the reservoir. Table 1-2 in the EPA report presents the average flow at various locations along the Snake and Columbia Rivers. In order to simulate different flow at each reservoir, the discharge in each reservoir was interpreted based on the river miles. Tables 3.3 and 3.4 present the estimated average discharge in each reservoir.

Based on Equation 9, the densimetric Froude number was computed for each segment of the reservoir. The results are presented in Tables 3.3 and 3.4. Figures 3.6 and 3.12 show the densimetric Froude numbers along the Snake and Columbia Rivers. Note that the value of the densimetric Froude number is very high for the upstream segments of the reservoir, but the value decreases significantly for the segments upstream of the dam. The following dams do not show this trend: Wells, Rock Island, Priest Rapids, The Dalles, and Bonneville Dams on the Columbia River. Consequently, except for those dams, this trend implies a completely mixed reservoir for the upstream reaches and a possible stratification for the reaches immediately upstream of the dam. Figure 3.12 shows that the densimetric Froude numbers for the segments between river mile 329 and 397 in the Columbia River are very high. This reach is the unimpounded Hanford reach.

It should be noted that the densimetric Froude numbers presented in Tables 3.3 and 3.4 are based on the average flow condition. These values are used to qualitatively represent the stratification potential at the deep sections of the reservoir, near the dam. As the flow decreases, the stratification potential increases. As the flow increases, the stratification potential decreases. It appears that the model assumption of no reservoir stratification is not applicable to some reservoirs on the Snake and Columbia Rivers. Therefore, the large reservoir system should consider both vertical and longitudinal spatial variation.

An earlier study performed by Jaske and Synoground (1970) concluded that the construction of reservoirs on the main stem of the Columbia River caused no significant changes in the average annual water temperature. The operation of Lake FDR, the reservoir behind the Grand Coulee Dam, delays the time of the peak summer temperature at the Rock Island Dam by about 30 days. Moore (1969) also concluded that both Lake FDR and Brownlee Reservoir on the Snake River caused cooling in the spring and summer caused by the release of hypolimnetic (deep stratified) water. The release of cooling water from a deep reservoir would further complicate the model simulation. Except for those dams discussed above, the effect of the release of cooling water from deep sections of a reservoir are an important component to the thermal behavior of the system and should not be ignored.

TABLE 3.1
CHANGE IN IMPOUNDMENT DUE TO HYDROELECTRIC PROJECTS IN THE SNAKE RIVER

				With Dam In Place			With Dam Removed Q@60,000 cfs			Percent of Change		
Begin RM	End RM	DX	RM	Depth (ft)	SA (acre)	V (acre-feet)	Depth (ft)	SA (acre)	V (acre-feet)	Depth (%)	SA (%)	V (%)
140.0	137.3	2.7	138.7	34.9	597	20825	6.5	713	4613	437	-16	351
137.3	134.6	2.7	136.0	34.9	597	20825	6.8	635	4194	416	-6	396
134.6	131.9	2.7	133.3	34.9	597	20825	8.0	293	2354	336	104	785
131.9	129.2	2.7	130.6	34.9	597	20825	9.7	269	2503	261	122	732
129.2	126.5	2.7	127.9	34.9	597	20825	13.5	212	2857	158	182	629
126.5	123.8	2.7	125.2	62.8	558	35044	14.2	218	3092	343	157	1033
123.8	121.1	2.7	122.5	62.8	558	35044	15.2	225	3434	313	148	920
121.1	118.4	2.7	119.8	62.8	558	35044	18.4	199	3628	242	181	866
118.4	116.3	2.1	117.4	73.6	524	38586	19.3	149	2865	282	252	1247
116.3	114.3	2.0	115.3	73.6	524	38586	16.0	172	2518	361	205	1432
114.3	112.3	2.0	113.3	73.6	524	38586	8.3	243	2027	787	116	1803
112.3	110.1	2.2	111.2	79.4	718	57027	12.4	258	3149	543	178	1711
110.1	107.9	2.2	109.0	79.4	718	57027	16.4	249	4068	384	189	1302
107.9	104.5	3.4	106.2	36.0	580	20883	15.5	391	6051	132	48	245
104.5	101.0	3.5	102.8	36.0	580	20883	10.8	446	4820	233	30	333
101.0	97.6	3.4	99.3	36.0	580	20883	8.7	409	3597	312	42	481
97.6	94.1	3.5	95.9	36.0	580	20883	9.1	409	3729	294	42	460
94.1	90.7	3.4	92.4	36.0	580	20883	12.8	392	5006	181	48	317
90.7	87.4	3.3	89.1	56.0	905	50635	11.7	399	4648	379	127	989
87.4	84.0	3.4	85.7	56.0	905	50635	11.2	425	4771	398	113	961
84.0	81.5	2.5	82.8	69.6	814	56622	10.9	447	3580	538	82	1482
81.5	78.9	2.6	80.2	69.6	814	56622	9.5	377	3516	632	116	1510
78.9	76.6	2.3	77.8	76.6	727	55658	7.6	375	2861	907	94	1845
76.6	74.2	2.4	75.4	76.5	728	55658	6.9	382	2638	1012	91	2010
74.2	70.8	3.4	72.5	78.5	956	75002	5.4	513	2754	1353	86	2624
70.8	67.5	3.3	69.2	49.4	518	25615	12.1	405	4717	307	28	443
67.5	64.2	3.3	65.9	49.4	518	25615	13.6	375	5095	264	38	403
64.2	60.9	3.3	62.6	49.4	518	25615	11.3	373	4232	336	39	505
60.9	57.6	3.3	59.3	49.4	518	25615	13.4	245	3173	270	112	707
57.6	54.2	3.4	55.9	49.4	518	25615	13.6	243	3219	265	113	696
54.2	50.7	3.5	52.5	72.4	717	51914	11.8	384	4515	514	87	1050
50.7	47.1	3.6	48.9	72.4	738	53397	9.6	495	4676	657	49	1042
47.1	44.6	2.5	45.9	78.7	735	57812	9.0	369	3313	776	99	1645
44.6	42.0	2.6	43.3	78.7	764	60125	8.9	412	3646	784	86	1549
42.0	38.3	3.7	40.2	34.0	752	25572	8.2	566	4644	317	33	451
38.3	34.7	3.6	36.5	34.0	752	25572	6.9	515	3542	393	46	622
34.7	31.0	3.7	32.9	34.0	752	25572	9.8	530	5166	247	42	395
31.0	27.4	3.6	29.2	34.0	752	25572	9.2	568	5231	268	32	389
27.4	23.7	3.7	25.6	34.0	752	25572	11.7	527	5661	190	43	352
23.7	21.1	2.6	22.4	58.0	772	44783	17.5	242	4220	231	220	961
21.1	18.5	2.6	19.8	58.0	772	44783	29.5	180	5080	97	329	782
18.5	16.0	2.5	17.3	58.0	772	44783	33.1	155	5133	75	397	773
16.0	13.9	2.1	15.0	70.0	574	40203	19.8	233	3386	253	146	1088
13.9	11.8	2.1	12.9	70.0	574	40203	7.8	326	2544	798	76	1480
11.8	9.7	2.1	10.8	70.0	574	40203	8.1	320	2586	763	80	1455

TABLE 3.2
CHANGE IN IMPOUNDMENT DUE TO HYDROELECTRIC PROJECTS IN THE COLUMBIA RIVER

				With Dam In Place			With Dam Removed Q@200,000 cfs			Percent of Change		
Begin RM	End RM	DX	RM	Depth (ft)	SA (acre)	V (acre-feet)	Depth (ft)	SA (acre)	V (acre-feet)	Depth (%)	SA (%)	V (%)
590.0	582.3	7.7	586.2	63.6	1108	70534	13.5	1013	13678	371	9	416
582.3	574.6	7.7	578.5	63.6	1130	71944	20.0	1907	38066	219	-41	89
574.6	568.0	6.6	571.3	63.6	969	61666	19.5	856	16686	226	13	270
568.0	560.5	7.5	564.3	63.6	1079	68701	26.2	762	19940	143	42	245
560.5	556.1	4.4	558.3	174.9	455	74804	36.6	461	16899	377	-1	343
556.1	550.5	5.6	553.3	199.7	525	104735	24.4	534	13017	718	-2	705
550.5	543.5	7.0	547.0	158.9	941	112033	11.3	781	8861	1301	21	1164
543.5	536.0	7.5	539.8	21.5	1997	42978	31.5	897	28265	-32	123	52
536.0	528.5	7.5	532.3	21.5	1997	42978	18.2	1035	18853	18	93	128
528.5	524.1	4.4	526.3	21.5	1172	25214	18.2	607	11061	18	93	128
524.1	521.0	3.1	522.6	21.5	825	17764	17.9	479	8590	20	72	107
521.0	516.6	4.4	518.8	21.5	1172	25214	17.6	682	12019	22	72	110
516.6	513.5	3.1	515.1	27.5	612	16262	27.4	420	11486	1	46	42
513.5	509.6	3.9	511.6	30.4	643	19559	27.4	528	14450	11	22	35
509.6	504.0	5.6	506.8	30.4	925	28137	34.2	616	21076	-11	50	34
504.0	496.7	7.3	500.4	30.4	1215	36962	21.6	669	14455	41	82	156
496.7	489.3	7.4	493.0	30.4	1232	37468	26.1	1108	28881	17	11	30
489.3	481.0	8.3	485.2	37.5	1862	74914	16.6	1213	20126	126	54	272
481.0	474.5	6.5	477.8	48.2	2004	96524	18.0	1156	20768	168	73	365
474.5	472.8	1.7	473.7	45.3	375	17340	21.3	272	5811	112	38	198
472.8	465.3	7.5	469.1	42.8	1100	47082	21.3	1201	25635	101	-8	84
465.3	461.1	4.2	463.2	42.8	616	26366	24.9	554	13779	72	11	91
461.1	456.9	4.2	459.0	42.8	623	26666	24.9	554	13779	72	12	94
456.9	452.1	4.8	454.5	37.3	865	30045	32.7	342	11189	14	153	169
452.1	447.2	4.9	449.7	22.5	1297	29193	21.8	791	17240	3	64	69
447.2	441.3	5.9	444.3	22.5	1561	35150	17.1	1182	20215	32	32	74
441.3	435.8	5.5	438.6	22.5	1456	32767	18.6	1254	23393	21	16	40
435.8	427.5	8.3	431.7	22.5	2197	49449	20.7	2402	49823	8	-9	-1
427.5	419.2	8.3	423.4	27.5	3906	113178	15.3	3792	58206	79	3	94
419.2	415.0	4.2	417.1	30.0	2362	71464	15.3	1919	29454	95	23	143
415.0	412.2	2.8	413.6	26.2	1050	27553	23.0	571	13156	14	84	109
412.2	409.5	2.7	410.9	26.2	1013	26569	23.0	550	12686	14	84	109
409.5	407.1	2.4	408.3	26.2	900	23617	14.3	825	11817	83	9	100
407.1	403.1	4.0	405.1	26.2	1500	39361	14.3	1374	19695	83	9	100
403.1	397.1	6.0	400.2	26.2	2250	59042	20.3	2379	48388	29	-5	22
397.1	392.4	4.7	394.8	19.1	841	16092	17.5	804	14073	9	5	14
392.4	386.7	5.7	389.6	17.6	1311	23104	16.3	1227	19989	8	7	16
386.7	382.1	4.6	384.4	20.4	811	16546	18.9	750	14164	8	8	17
382.1	377.4	4.7	379.8	14.2	1128	15970	12.8	1111	14169	11	2	13
377.4	371.6	5.8	374.5	10.9	2442	26702	10.0	2339	23339	9	4	14
371.6	364.4	7.2	368.0	17.7	1625	28804	15.9	1593	25395	11	2	13
364.4	358.3	6.1	361.4	24.4	877	21419	22.2	844	18722	10	4	14
358.3	353.6	4.7	356.0	16.3	1293	21123	14.9	1230	18338	9	5	15
353.6	346.3	7.3	350.0	14.4	1961	28159	12.9	1938	24993	12	1	13
346.3	339.5	6.8	342.9	16.2	1604	25965	15.5	1402	21711	5	14	20
339.5	333.6	5.9	336.6	21.7	2085	45175	19.5	2043	39872	11	2	13
333.6	329.4	4.2	331.5	19.2	1840	35329	17.6	1739	30668	9	6	15

TABLE 3.2 Cont'd.

				With Dam In Place			With Dam Removed Q@200,000 cfs			Percent of Change		
Begin RM	End RM	DX	RM	Depth (ft)	SA (acre)	V (acre-feet)	Depth (ft)	SA (acre)	V (acre-feet)	Depth (ft)	Depth (ft)	SA (acre)
329.4	324.0	5.4	326.7	14.3	4554	64947	12.9	4456	57322	11	2	13
324.0	319.0	5.0	321.5	22.3	5065	113097	14.8	1316	19427	51	285	482
319.0	315.0	4.0	317.0	22.3	4052	90478	14.8	1053	15542	51	285	482
315.0	310.0	5.0	312.5	38.2	2320	82718	14.8	1316	19427	159	76	326
310.0	305.0	5.0	307.5	40.4	1946	78575	15.1	1540	23284	167	26	237
305.0	300.0	5.0	302.5	44.2	2040	91522	9.7	1841	17787	358	11	415
300.0	295.0	5.0	297.5	57.9	2375	137425	10.0	1734	17363	478	37	691
295.0	290.0	5.0	292.5	44.2	2329	55250	12.3	1506	18547	259	55	198
290.0	285.0	5.0	287.5	23.7	2329	55250	15.4	1393	21509	54	67	157
285.0	280.0	5.0	282.5	23.7	2329	55250	12.8	1603	20486	85	45	170
280.0	275.0	5.0	277.5	23.7	2329	55250	31.0	943	29275	-24	147	89
275.0	270.0	5.0	272.5	24.2	4500	109337	12.5	1018	12693	94	342	761
270.0	265.0	5.0	267.5	24.4	5617	137200	10.0	2103	21126	143	167	549
265.0	260.0	5.0	262.5	40.8	3435	140155	17.0	1294	22003	140	165	537
260.0	255.0	5.0	257.5	44.2	3228	141072	10.9	1378	14979	306	134	842
255.0	250.0	5.0	252.5	51.3	2789	143020	17.4	1443	25156	194	93	469
250.0	245.0	5.0	247.5	58.7	3185	187621	16.7	1774	29650	251	79	533
245.0	240.0	5.0	242.5	69.1	2525	172162	11.4	1501	17064	508	68	909
240.0	235.0	5.0	237.5	73.9	2344	173672	17.0	1526	25980	334	54	568
235.0	230.0	5.0	232.5	78.9	2577	203217	26.0	1333	34637	204	93	487
230.0	225.0	5.0	227.5	73.7	2917	214560	9.5	1259	11950	677	132	1695
225.0	220.0	5.0	222.5	80.7	2705	215508	12.6	1264	15910	541	114	1255
220.0	215.0	5.0	217.5	83.6	2298	195512	26.4	1366	36106	216	68	441
215.0	210.0	5.0	212.5	35	1777	62144	17.8	1108	19768	96	60	214
210.0	205.0	5.0	207.5	35	1777	62144	17.4	1386	24157	101	28	157
205.0	200.0	5.0	202.5	35	1777	62144	19.8	1518	30054	77	17	107
200.0	195.0	5.0	197.5	35	1777	62144	19.8	1518	30054	77	17	107
195.0	190.0	5.0	192.5	34.6	1732	60021	36.3	1315	47683	-4	32	26
190.0	185.0	5.0	187.5	33.9	1625	55067	15.5	984	15254	119	65	261
185.0	180.0	5.0	182.5	33.9	1625	55067	16.5	1519	25035	106	7	120
180.0	175.0	5.0	177.5	33.9	1625	55067	40.6	1072	43585	-17	52	26
175.0	170.0	5.0	172.5	33.9	1625	55067	24.7	1522	37548	37	7	47
170.0	165.0	5.0	167.5	33.5	1712	57253	16.5	1957	32252	104	-13	78
165.0	160.0	5.0	162.5	31.5	2246	70678	13.7	2067	28310	130	9	150
160.0	155.0	5.0	157.5	31.5	2246	70678	13.7	2063	28310	130	9	150
155.0	150.0	5.0	152.5	31.5	2246	70678	13.6	1086	14728	132	107	380
150.0	146.1	3.9	148.1	31.5	1752	55129	13.6	847	11488	132	107	380
146.1	140.0	6.1	143.1	31.5	2740	86227	14.2	480	6823	121	471	1164

TABLE 3.3
AVERAGE FLOW AND DENSIMETRIC FROUDE NUMBER IN SNAKE RIVER WITH DAMS

Dam	Begin RM	End RM	RM	Depth (ft)	Average Flow (cfs)	Densimetric Froude No.
	140.0	137.3	138.65	34.9	38492	5.55
	137.3	134.6	135.95	34.9	38807	5.59
	134.6	131.9	133.25	34.9	39123	5.64
	131.9	129.2	130.55	34.9	39438	5.69
	129.2	126.5	127.85	34.9	39754	5.73
	126.5	123.8	125.15	62.8	40069	1.91
	123.8	121.1	122.45	62.8	40385	1.92
	121.1	118.4	119.75	62.8	40700	1.94
	118.4	116.3	117.35	73.6	40945	1.17
	116.3	114.3	115.3	73.6	41179	1.12
	114.3	112.3	113.3	73.6	41413	1.13
	112.3	110.1	111.2	79.4	41670	0.79
Lower Granite	110.1	107.9	109	79.4	41927	0.79
	107.9	104.5	106.2	36.0	42324	7.42
	104.5	101	102.75	36.0	42733	7.72
	101.0	97.6	99.3	36.0	43130	7.56
	97.6	94.1	95.85	36.0	43539	7.86
	94.1	90.7	92.4	36.0	43936	7.71
	90.7	87.4	89.05	56.0	44322	2.00
	87.4	84	85.7	56.0	44719	2.08
	84.0	81.5	82.75	69.6	45011	1.11
	81.5	78.9	80.2	69.6	45315	1.16
	78.9	76.6	77.75	76.6	45584	0.95
	76.6	74.2	75.4	76.5	45864	1.00
Little Goose	74.2	70.8	72.5	78.5	46261	1.04
	70.8	67.5	69.15	49.4	46647	4.71
	67.5	64.2	65.85	49.4	47033	4.75
	64.2	60.9	62.55	49.4	47418	4.79
	60.9	57.6	59.25	49.4	47804	4.83
	57.6	54.2	55.9	49.4	48201	5.02
	54.2	50.7	52.45	72.4	48610	1.76
	50.7	47.1	48.9	72.4	49030	1.77
	47.1	44.6	45.85	78.7	49322	1.05
Lower Monumental	44.6	42	43.3	78.7	49626	1.06
	42.0	38.3	40.15	34.0	50059	8.26
	38.3	34.7	36.5	34.0	50479	8.11
	34.7	31	32.85	34.0	50911	8.40
	31	27.4	29.2	34.0	51332	8.24
	27.4	23.7	25.55	34.0	51764	8.54
	23.7	21.1	22.4	58.0	52068	2.02
	21.1	18.5	19.8	58.0	52372	2.03
	18.5	16	17.25	58.0	52664	1.97
	16.0	13.9	14.95	70.0	52909	1.53
	13.9	11.8	12.85	70.0	53155	1.54
Ice Harbor	11.8	9.7	10.75	70.0	53400	1.54

TABLE 3.4
AVERAGE FLOW AND DENSIMETRIC FROUDE NUMBER IN COLUMBIA RIVER WITH DAMS

Dam	Begin RM	End RM	RM	Depth (ft)	V (acre-feet)	Average Flow (cfs)	Densimetric Froude No.
	590.0	584.9	587.45	63.6	46717	108374	7.21
	584.9	579.9	582.4	63.6	46717	108448	7.07
	579.9	574.8	577.35	63.6	46717	108524	7.22
	574.8	569.8	572.3	63.6	46717	108598	7.08
	569.8	564.7	567.25	63.6	46717	108674	7.23
	564.7	559.7	562.2	63.6	46717	108748	7.09
	559.7	554.8	557.25	199.7	91643	108821	1.13
	554.8	549.9	552.35	199.7	91643	108894	1.13
Chief Joseph	549.9	545.1	547.5	199.7	91643	108965	1.11
	545.1	539.2	542.15	21.5	33810	109052	34.30
	539.2	533.3	536.25	21.5	33810	109139	34.33
	533.3	527.4	530.35	21.5	33810	109226	34.35
	527.4	521.5	524.45	21.5	33810	109313	34.38
Wells	521.5	515.6	518.55	21.5	33810	109400	34.41
	515.6	505.1	510.35	30.4	52658	110352	28.06
	505.1	494.7	499.9	30.4	52658	111295	28.03
	494.7	484.3	489.5	30.4	52658	112238	28.26
	484.3	480.8	482.55	48.2	52604	112556	6.03
	480.8	477.3	479.05	48.2	52604	112874	6.05
	477.3	473.7	475.5	48.2	52604	113200	6.24
Rocky Reach	473.7	466.9	470.3	42.8	42688	114238	16.49
	466.9	460.1	463.5	42.8	42688	115277	16.64
Rock Island	460.1	453.4	456.75	42.8	42688	116300	16.54
	453.4	424.2	438.8	22.5	173964	117389	33.95
Wanapum Priest	424.2	415.8	420	30.8	157110	117702	7.91
Rapid	415.8	397.1	406.45	26.2	184014	118400	17.79
	397.1	392.4	394.75	19.1	16092	120060	71.11
	392.4	386.7	389.55	17.6	23104	122072	66.29
	386.7	382.1	384.4	20.4	16546	123696	65.40
	382.1	377.4	379.75	14.2	15970	125356	101.03
	377.4	371.6	374.5	10.9	26702	127404	98.16
	371.6	364.4	368	17.7	28804	129946	71.08
	364.4	358.3	361.35	24.4	21419	132100	59.76
	358.3	353.6	355.95	16.3	21123	133760	70.67
	353.6	346.3	349.95	14.4	28159	136338	95.48
	346.3	339.5	342.9	16.2	25965	138739	87.07
	339.5	333.6	336.55	21.7	45175	140822	32.93
	333.6	329.4	331.5	19.2	35329	142305	34.17
	329.4	324.0	326.7	14.3	64947	144212	32.61
	324.0	314.4	319.2	22.3	217147	147602	11.33
	314.4	301.1	307.75	40.4	209010	152298	9.31
McNary	301.1	292.0	296.55	57.9	250113	155512	3.79
	292.0	273.3	282.65	23.7	206635	162115	23.99
	273.3	265.0	269.15	24.4	227752	165046	9.55
	265.0	256.6	260.8	40.8	235460	168012	5.70
	256.6	249.1	252.85	51.3	214530	170660	4.51
	249.1	243.7	246.4	60.3	213204	172567	2.81
	243.7	236.3	240	72.2	241671	175180	2.88
	236.3	229.1	232.7	78.9	292632	177722	2.15

TABLE 3.4 – Cont'd.

Dam	Begin RM	End RM	RM	Depth (ft)	V (acre-feet)	Average Flow (cfs)	Densimetric Froude No.
	229.1	222.3	225.7	72.6	295188	180124	2.22
John Day	222.3	215.6	218.95	90.2	286356	182490	1.84
The Dalles	215.6	191.5	203.55	35.0	299532	191000	17.05
	191.5	165.7	178.6	33.9	284148	200110	20.80
Bonneville	165.7	145.5	155.6	31.5	285538	207243	18.07

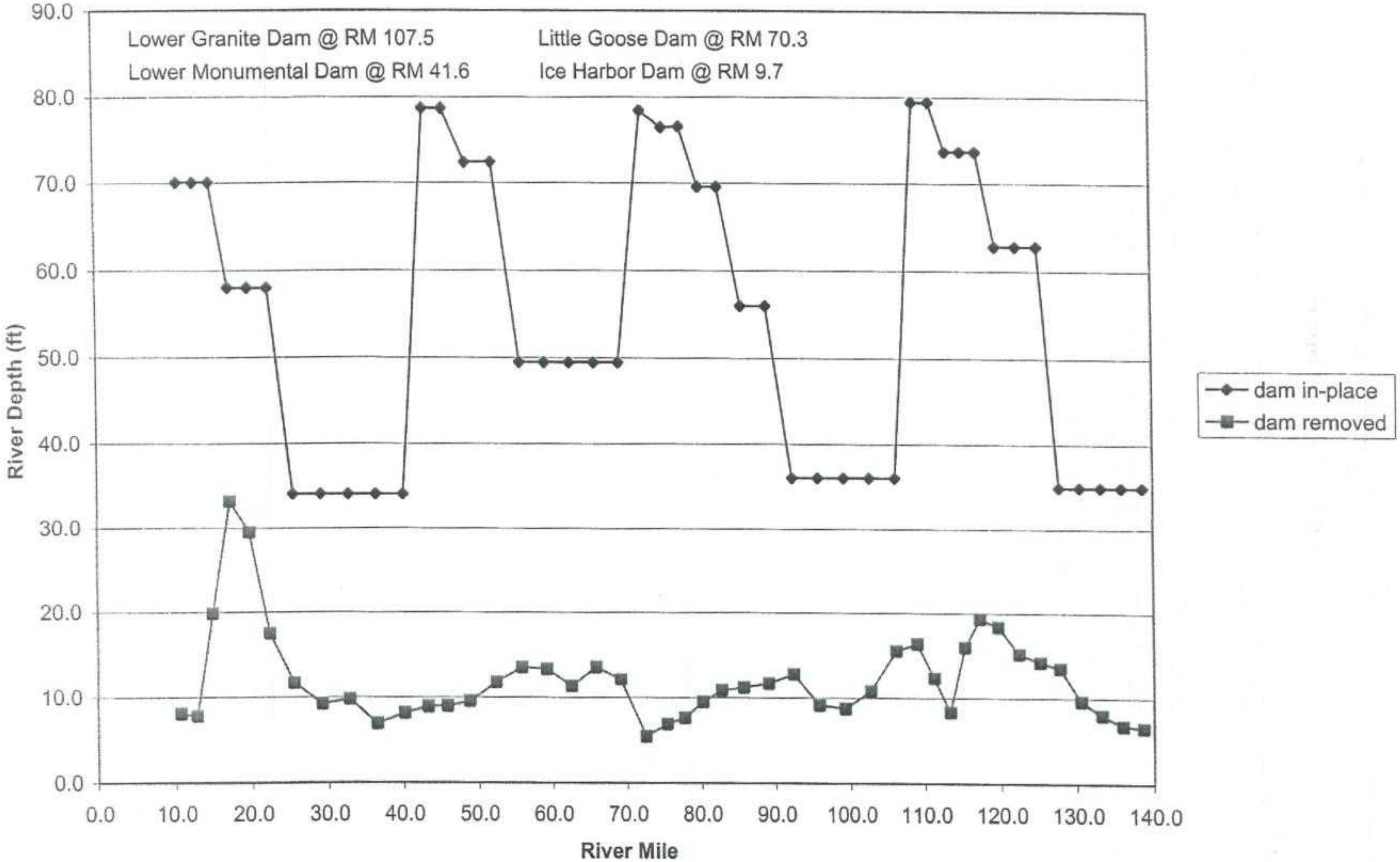


Figure 3.1 – River Mile vs. River Depth (Snake River)

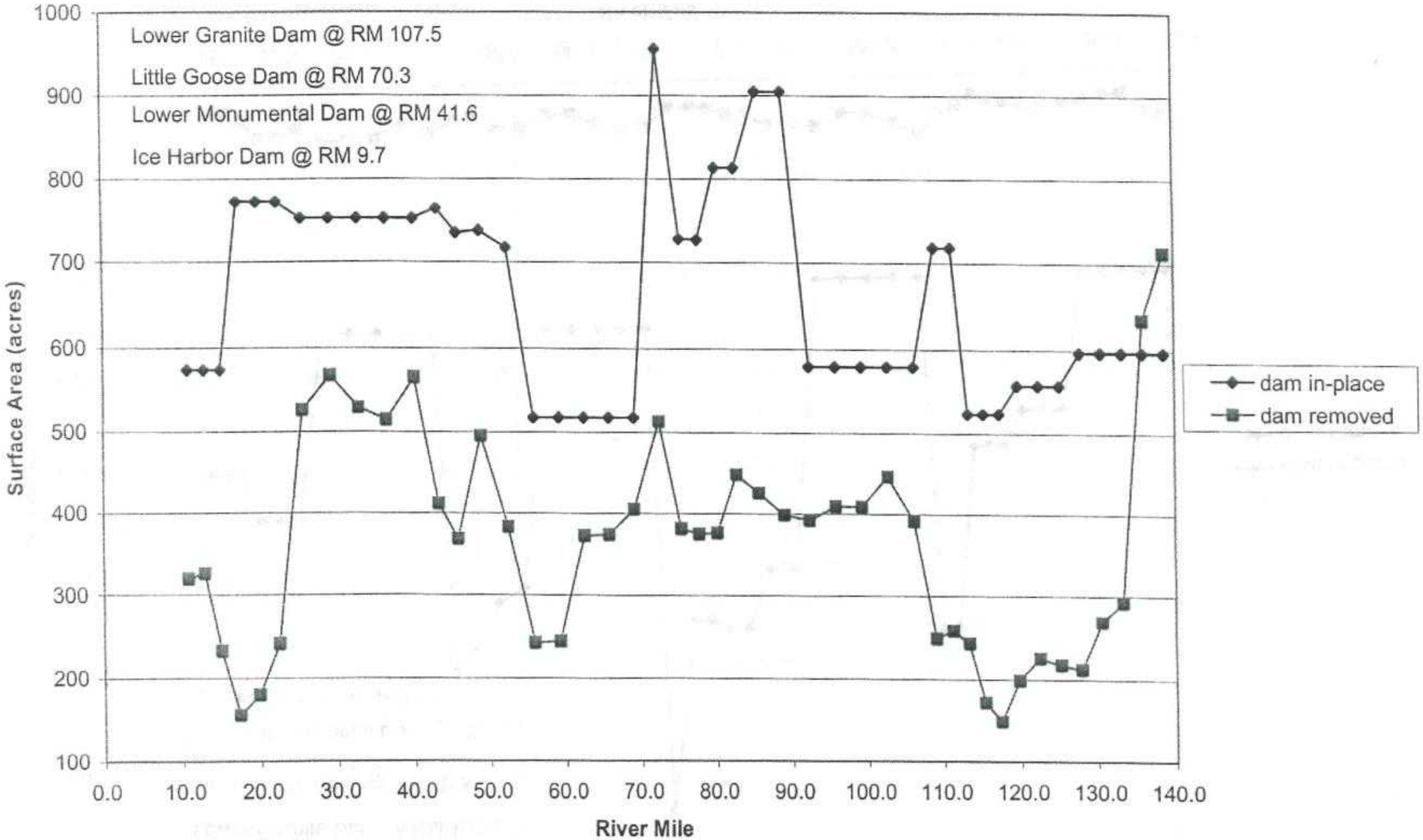


Figure 3.2 – River Mile vs. Surface Area (Snake River)

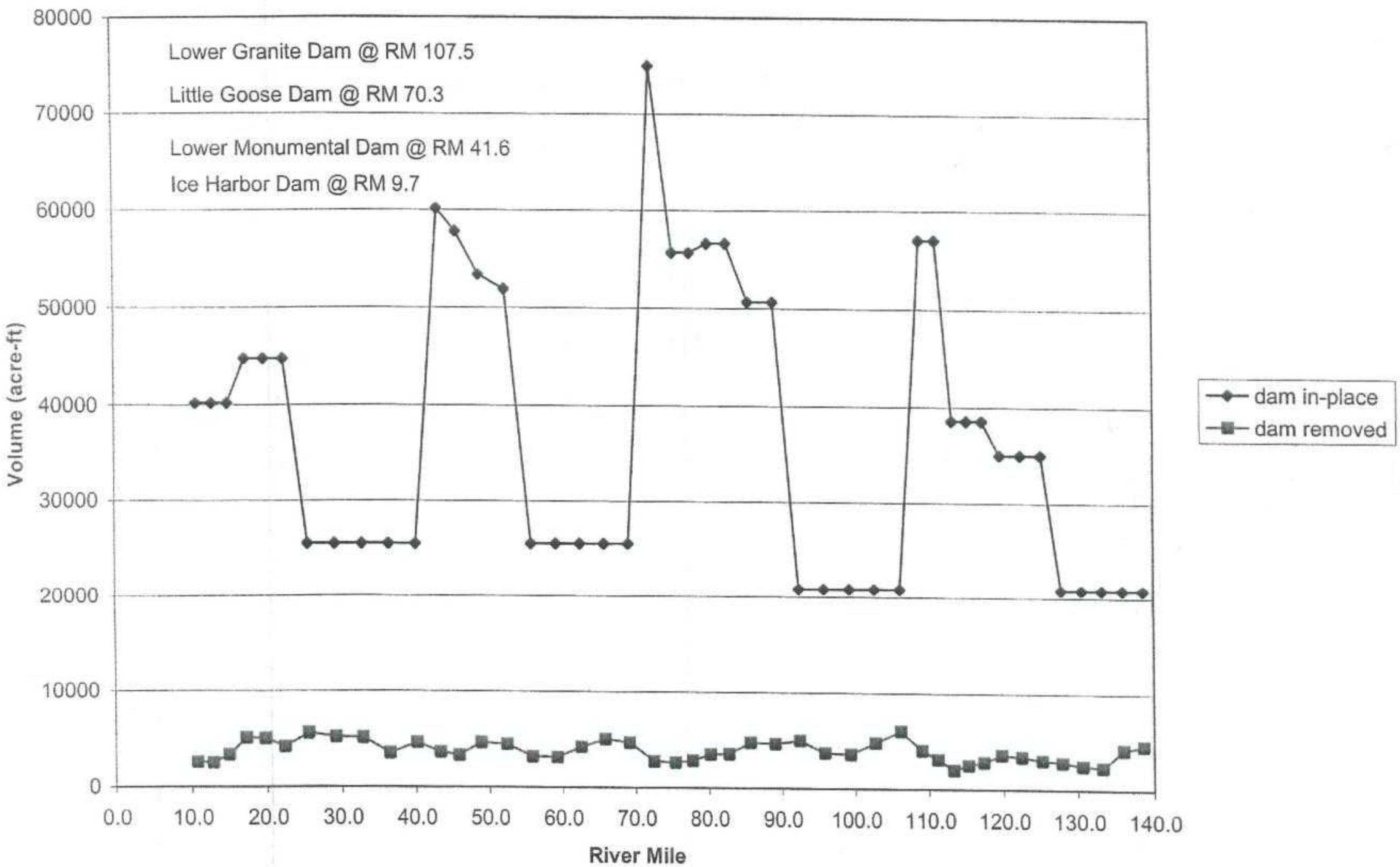


Figure 3.3 – River Mile vs. Volume (Snake River)

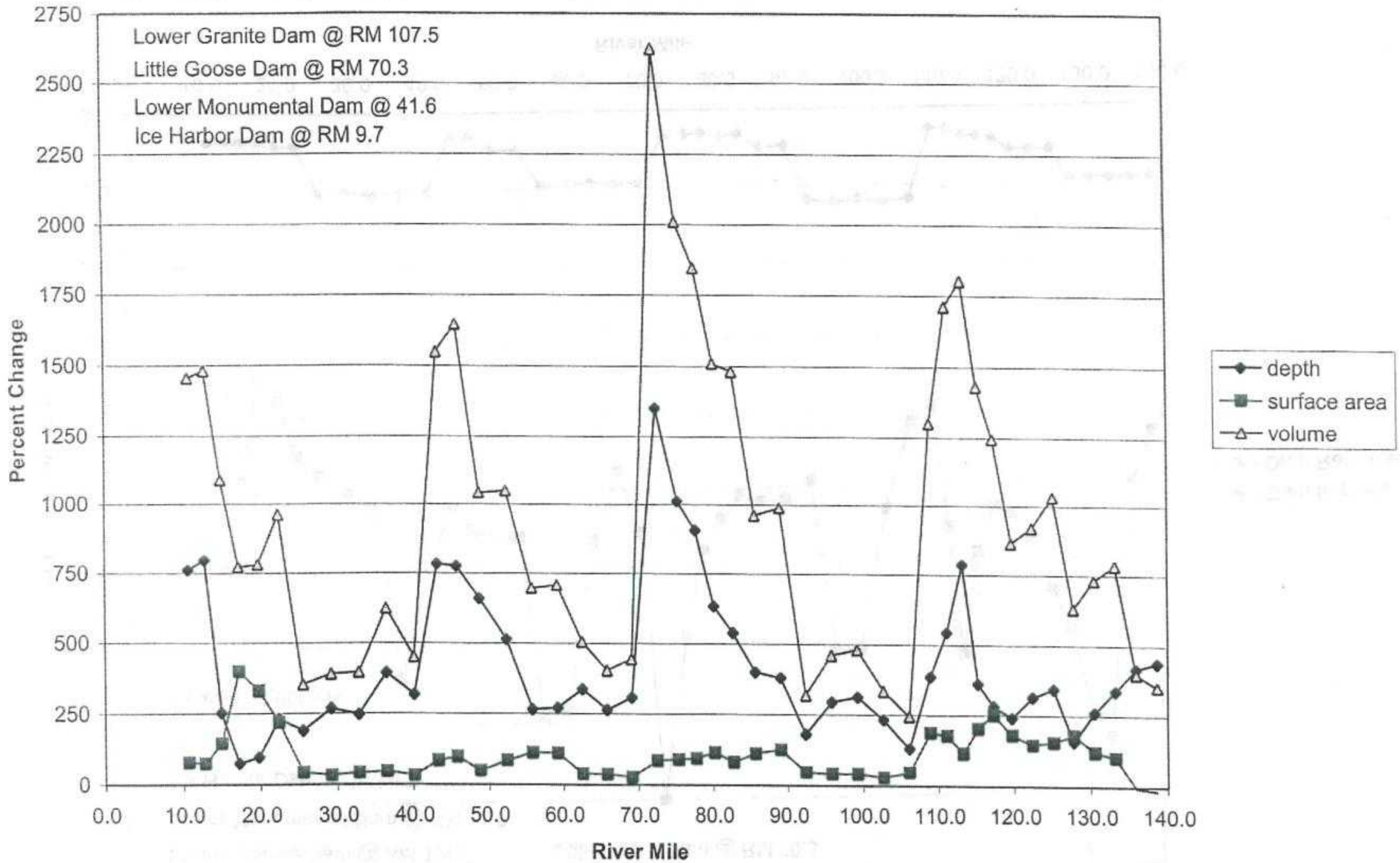


Figure 3.4 – River Mile vs. Percent Change (Snake River)

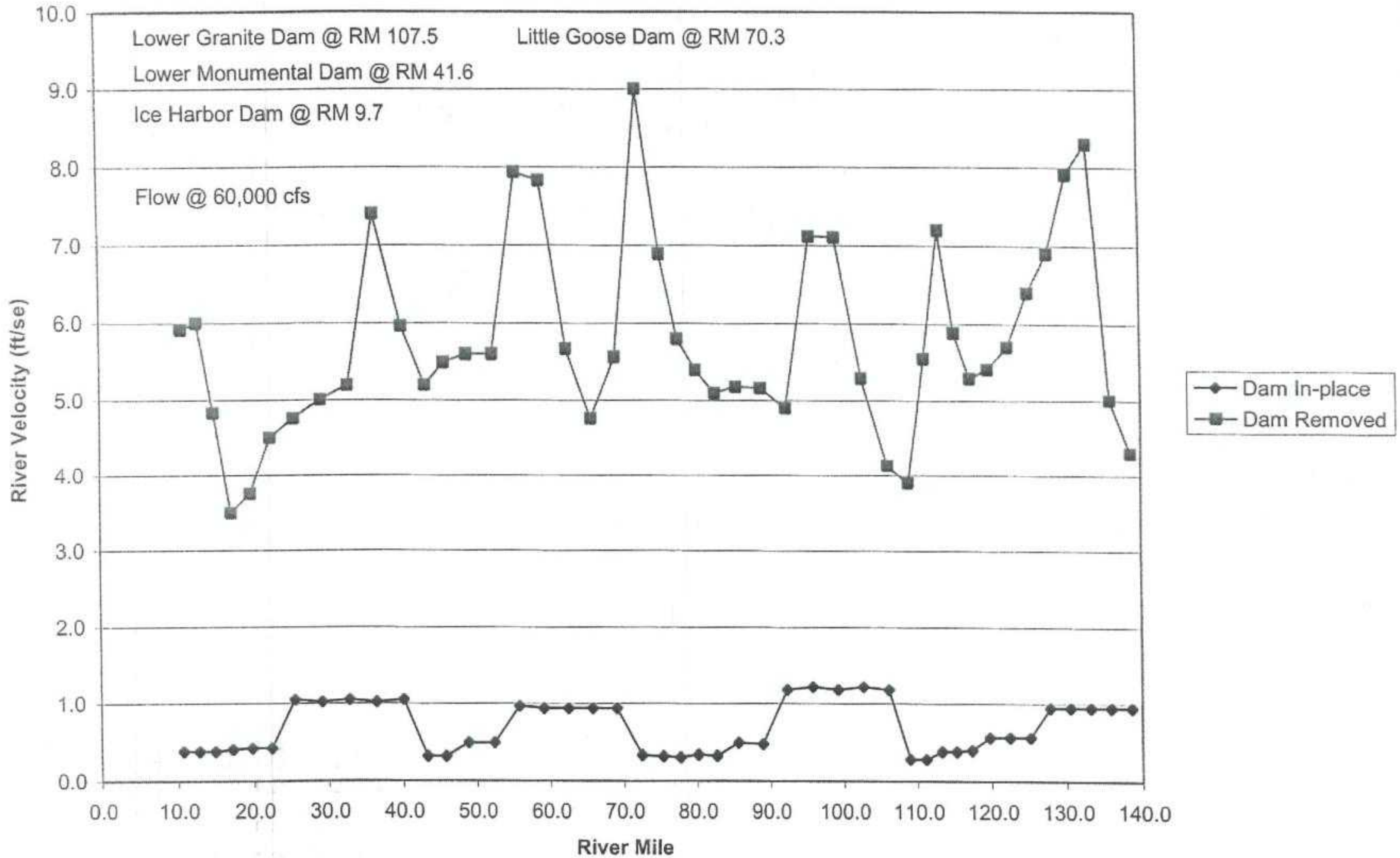


Figure 3.5 – River Mile vs. River Velocity (Snake River)

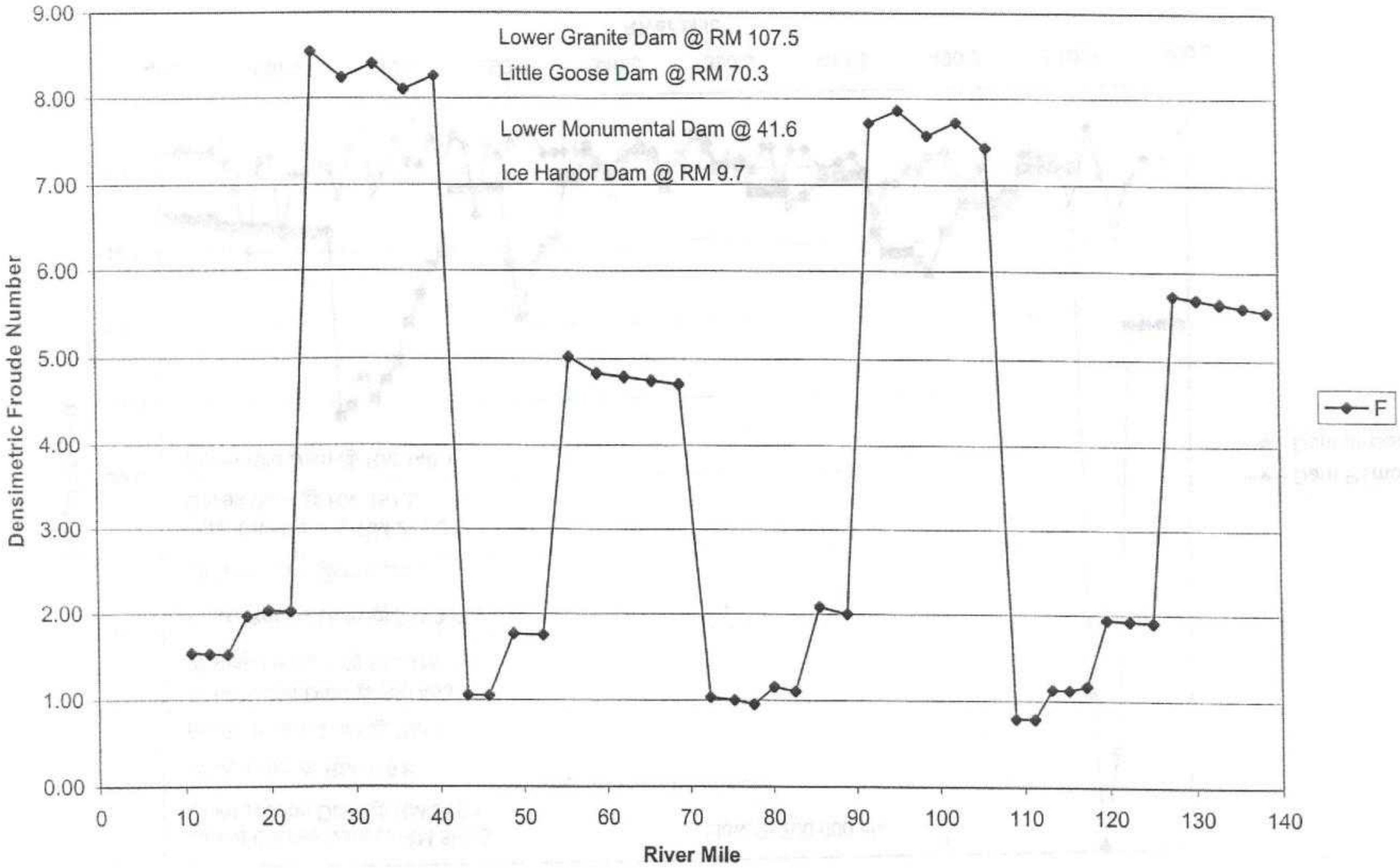


Figure 3.6 – River Mile vs. Densimetric Froude Number (Snake River)

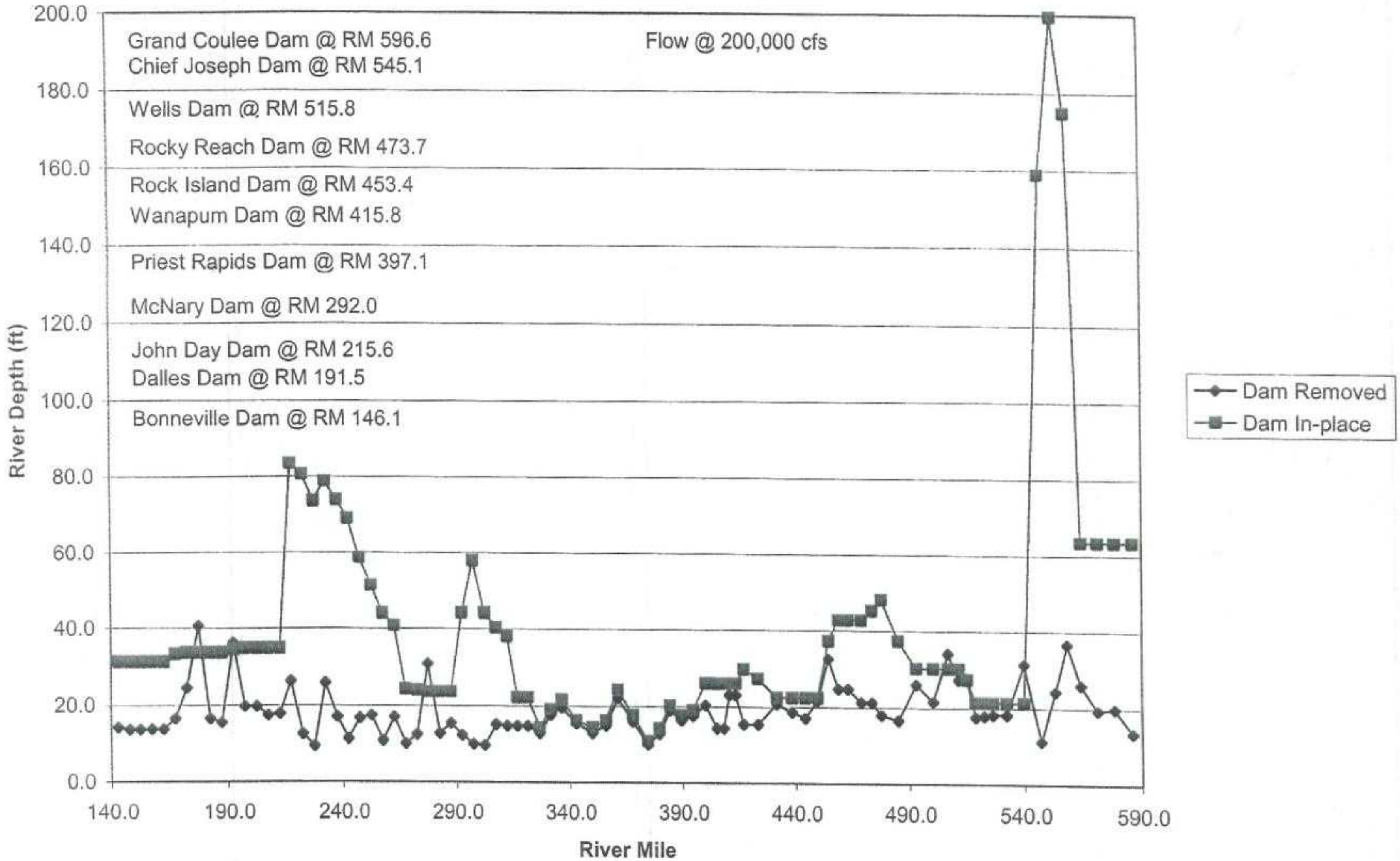


Figure 3.7 – River Mile vs. River Depth (Columbia River)

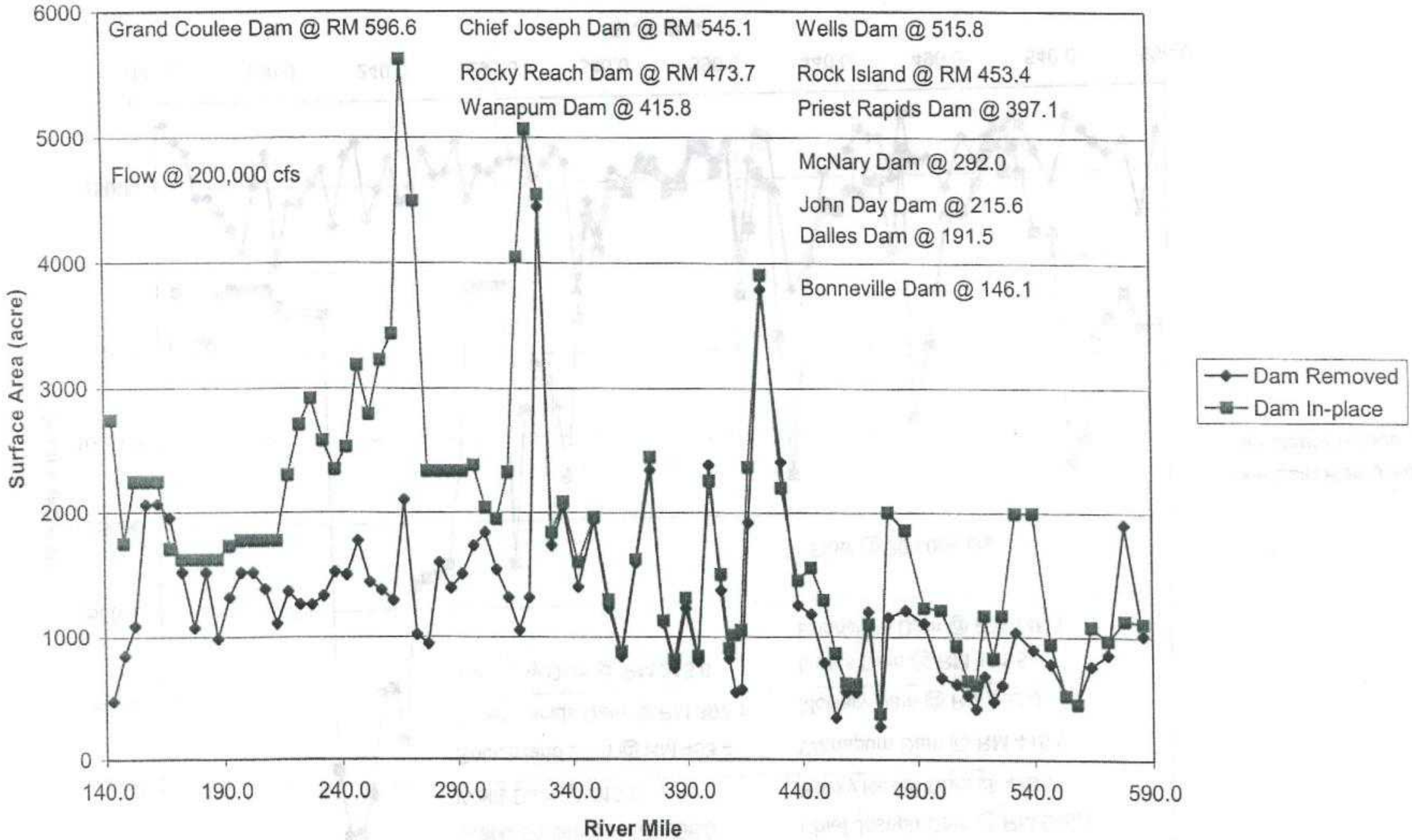


Figure 3.8 – River Mile vs. Surface Area (Columbia River)

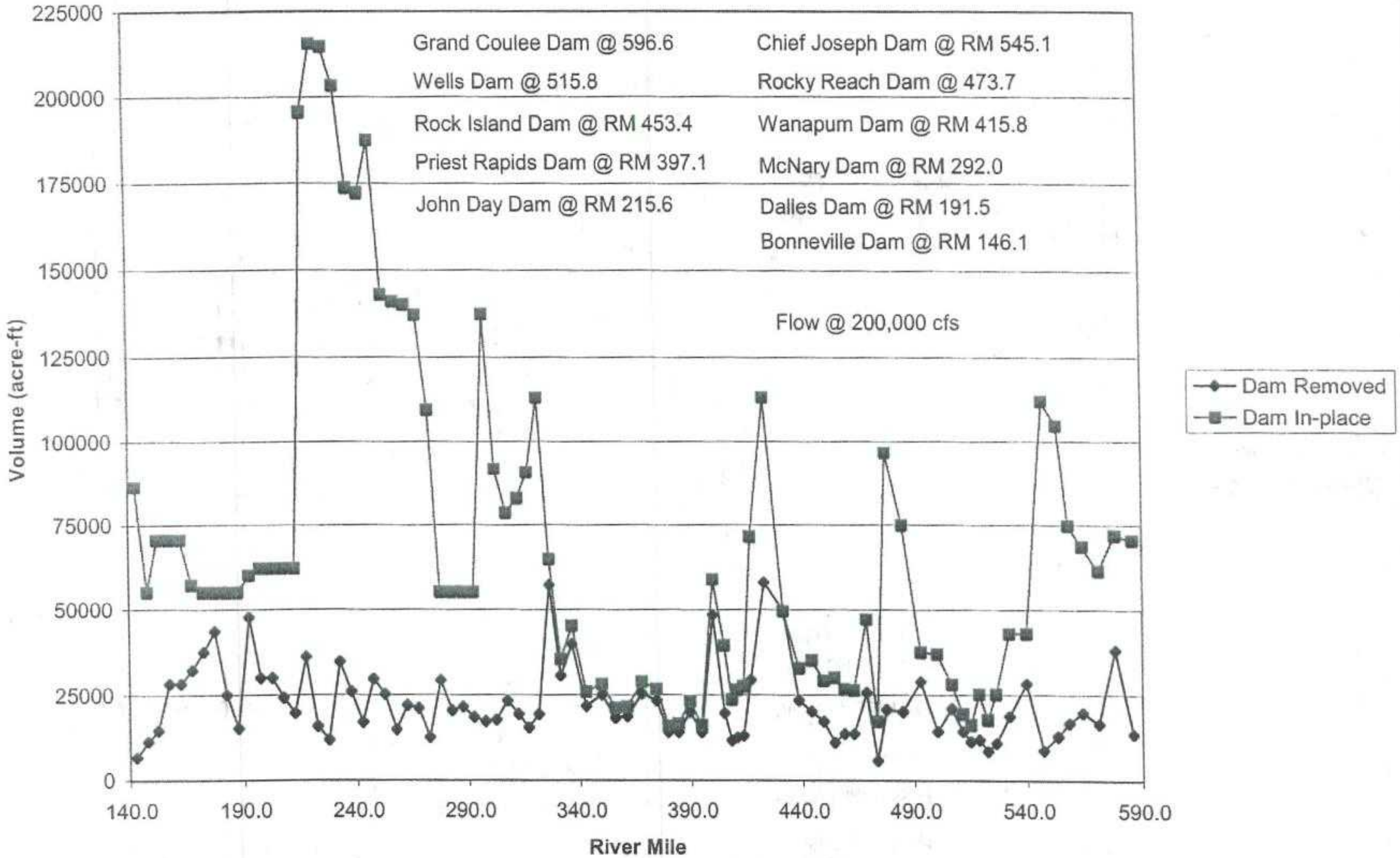


Figure 3.9 – River Mile vs. Volume (Columbia River)

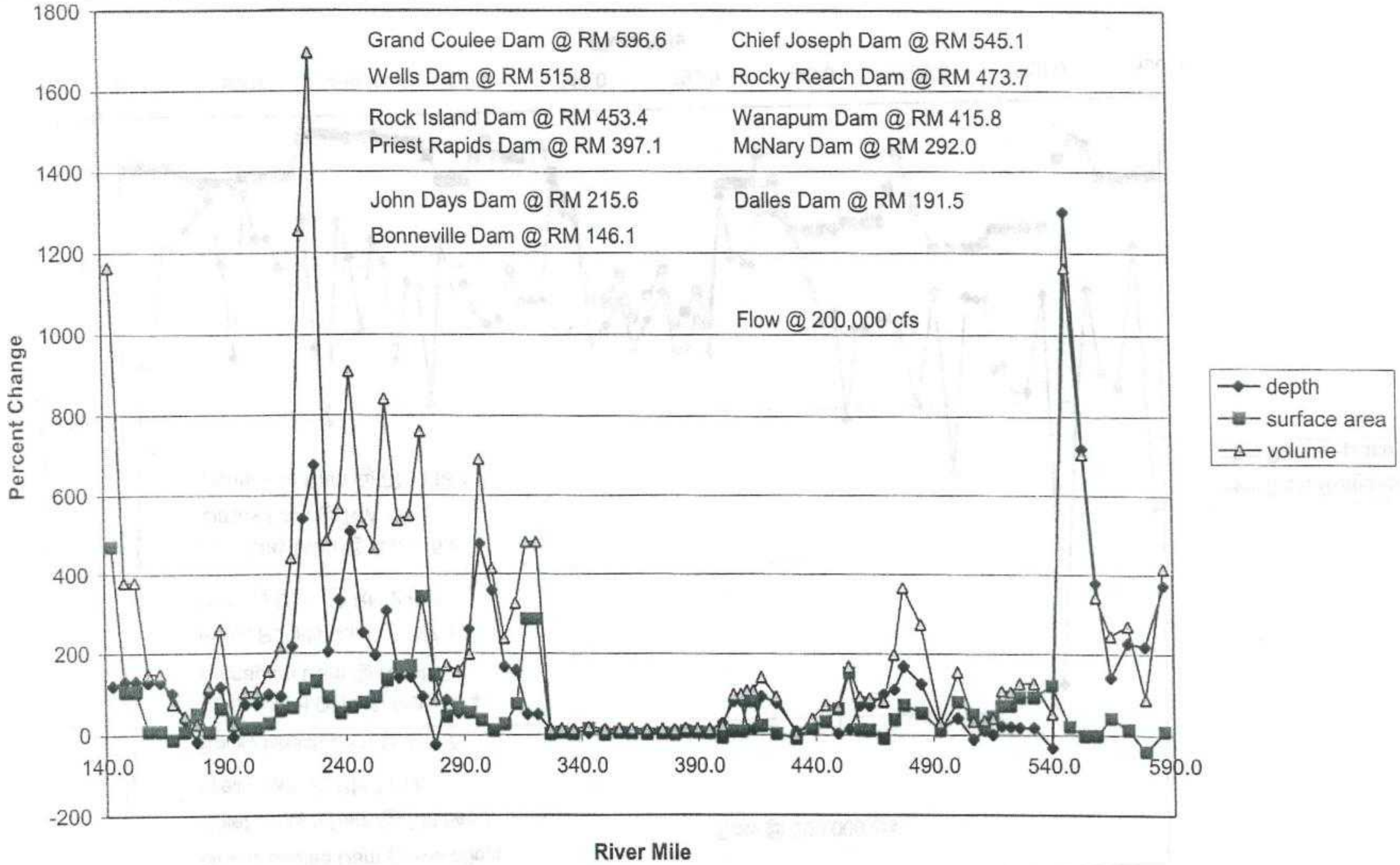


Figure 3.10 – River Mile vs. Percent Change (Columbia River)

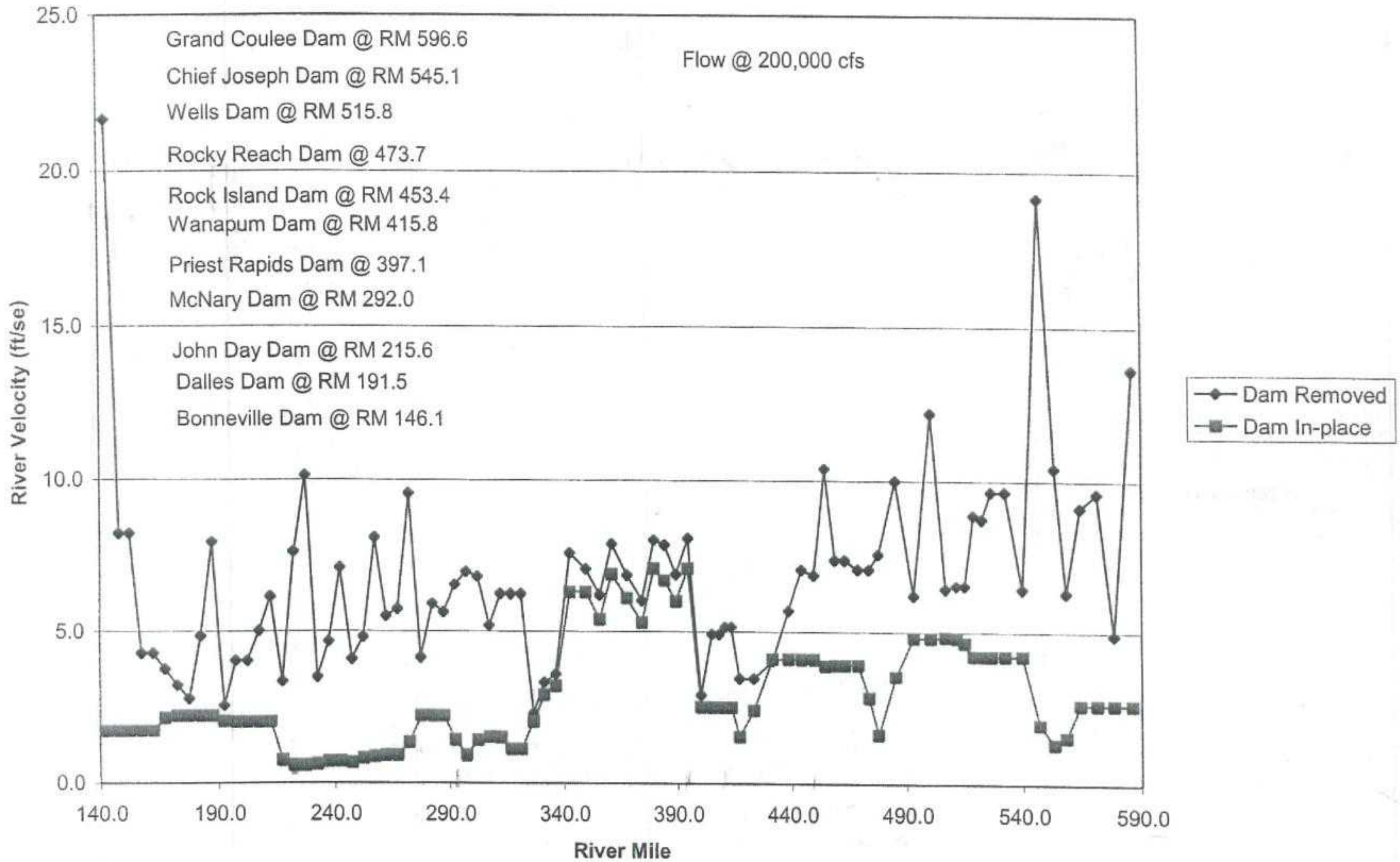


Figure 3.11 – River Mile vs. River Velocity (Columbia River)

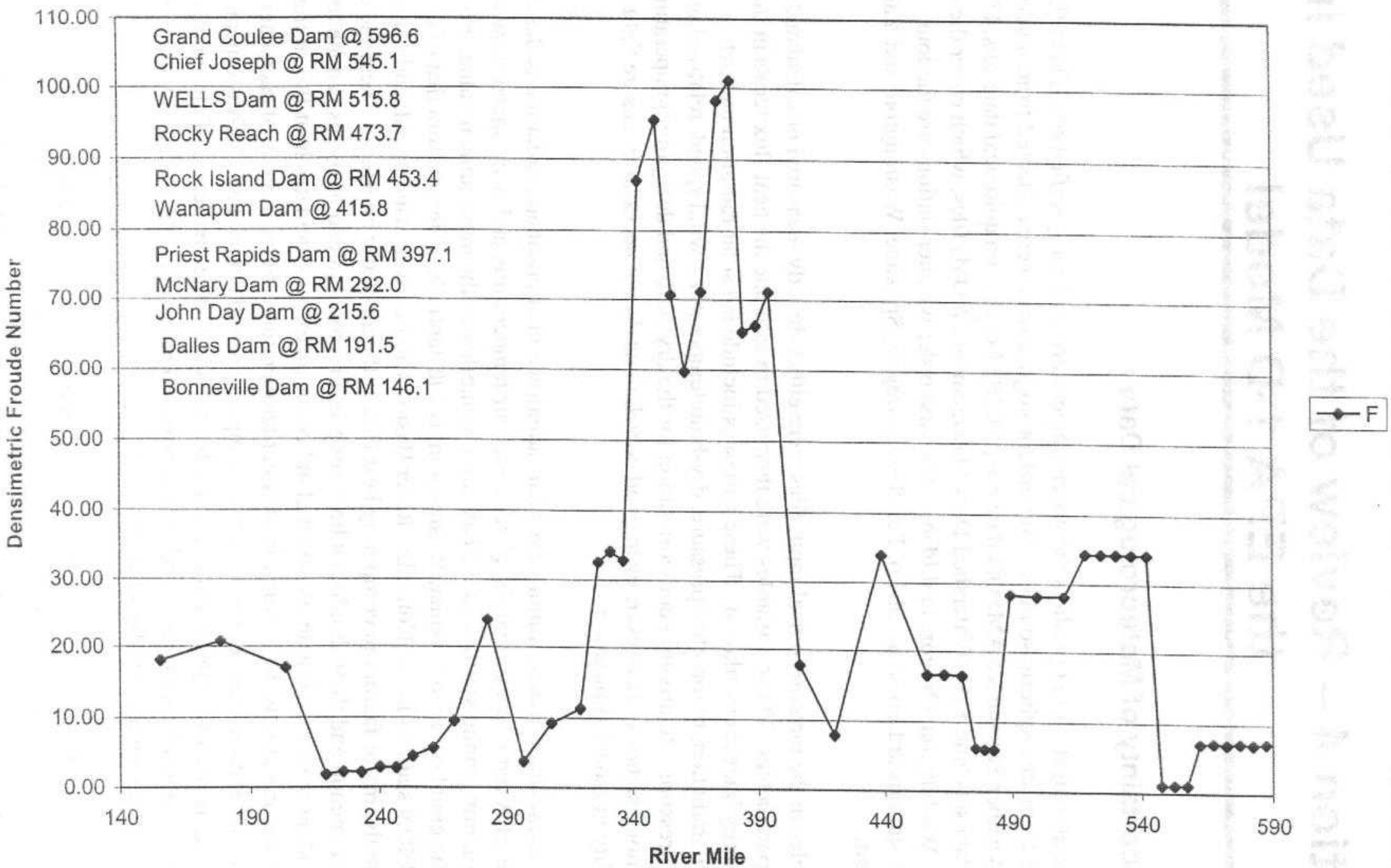


Figure 3.12 – River Mile vs. Densimetric Froude Number (Columbia River)

Section 4 – Review of the Data Used in the EPA 1-D Model

4.1 Uncertainty of Meteorological Data

The 1-D heat budget model predicts the water temperature under a specified set of heat flux conditions from atmospheric sources. The meteorological data were collected from several sources; Weather Service's SAMSON data sets, NCDC Local Climatological data sets, USBR's AgriMet data sets, and EPA Watershed Data Management (WDM) files, which cover the states of Alaska, Washington, Oregon, and Idaho. The first order weather stations are the four SAMSON stations at Lewiston, Idaho; Pendleton, Oregon; Spokane, Washington; and Yakima, Washington.

The variables in the meteorological input files were either directly measured or calculated from surrogate parameters. These variables were then used to estimate the heat flux terms in the thermal energy budget calculation. These variables include net solar radiation and net atmospheric radiation, barometric pressure, dry-bulb temperature, wind speed, relative humidity, and vapor pressure. Relatively good correlation for the dry-bulb and dew point temperature were claimed among stations. However, even good correlations do not necessarily ensure tight predictability in model simulation.

One of the parameters in determining the solar radiation and atmospheric radiation is the cloud cover. The EPA report states that the cloud cover, air temperature, and wind speed show a much lower correlation among stations as well as more variability in the mean annual value. For example, the cloud cover in Yakima, Washington, is substantially different from that of other three SAMSON stations in the Columbia River Basin. Cloud cover, wind speed, and vapor pressure are the major factors in computing heat flux at the air-water interface. These factors are a local phenomenon and they should not be treated as a regional phenomenon as is done by the 1-D heat budget model. Using an incorrect cloud cover index miscalculates heat flux at the air-water interface and affects the prediction of water temperature. In our review of such data, it appears that correlations are very weak between input data and actual data. This is especially true of relative humidity, vapor pressure, and solar radiation. The prediction of air temperature between different nearby stations, which had a strong correlation of .88, could only predict temperature within a range of plus or minus 10°C.

Another source of error is the uncertainty of using an incorrect wind speed. In addition to the local influence on wind speed, further adjustment on the wind speed is needed prior to heat flux calculation. Wind speed is normally recorded over the land at a certain elevation. The wind speed varies with elevation. The elevation at four weather stations ranges from El. 1064 at Yakima, Washington, to El. 2356 at Spokane, Washington. However, the headwater elevation in the Snake River ranges from El. 746 at Lower Granite Dam to El. 580 at Ice Harbor Dam. The headwater elevation in the Columbia River ranges from El. 900 at Grand Coulee Dam to El. 82 at Bonneville Dam. Therefore, the recorded wind speeds at four weather stations may produce unreliable values for the Snake and Columbia River Basins. Another adjustment on wind speed is to convert the recorded overland wind speed to over-water wind speed. Under the same atmospheric conditions, the over-water wind speed is generally faster than the overland wind speed.

The parameters derived for the system model are linked to the data input files from the observation model. The system model is then used to predict the water temperature. The variation and uncertainty in data quality makes the task of quantifying data measurements bias and assessing error a difficult one. Therefore, the uncertainty in cloud cover, wind speed and evaporation rate would simulate unreliable parameters for the system model. Furthermore, the choice of appropriate meteorological stations to provide the data for the Snake and Columbia river basins must consider the spatial and temporal variations due to local phenomenon. The constraint of a limited number of stations with complete data creates additional uncertainty and, thus, affects the parameters for computing the heat flux exchange at the air-water interface. We demonstrate the weakness in the data set in detail in the following analysis of the data set used to build the model.

4.2 Meteorological Source Data Evaluation

In our critique of the initial draft of the EPA Model (Harza, 1999), we noted that the primary problem we could discern was the inadequacy of the database to provide accurate (realistic) or precise (repeatable) thermal model predictions. The Kalman Filter, a sophisticated regression technique, was used to fill in missing non-linear data. At that time, an in-depth examination of the actual source data used in the model was beyond the scope of that review. The objective of this exercise in this second review of the "improved" EPA model was to quantify and map the spatial and temporal extent of the source data used to create the meteorological input files for the EPA model. It is the adequacy of these data that will determine the precision, the predictability, and in the end, the reliability of the EPA Model.

We duplicated EPA's process and downloaded source data from the National Climatic Data Center (NCDC) web site (EPA's source) and generated our own Microsoft Access database that was used for this assessment. We did this because the exact extent of the database is not evident in the model or its description. From the list of all measurements contained in the NCDC files, we extracted a subset that includes parameters needed to generate the EPA model "*.hot" input files (Table 4.1). The source-list of weather stations providing these variables is shown in Table 4.2.

TABLE 4.1
LIST OF MEASUREMENT VARIABLES USED TO EVALUATE EPA'S MODEL TAKEN FROM THE SOURCES CITED BY EPA

Elem Index	Elem	Description
2	AWND	Average Daily Wind Speed
5	DPTP	Average Daily Dew - Point Temperature
9	EVAP	Daily Evaporation
16	MNPN	Daily Minimum Temperature of Water in an Evaporation Pan
17	MNRH	Minimum Relative Humidity
18	MNTP	Average Temperature (begin 1984), (Max Temp + Min Temp)/2, in whole degrees Fahrenheit
19	MXPN	Daily Maximum Temperature of Water in an Evaporation Pan
20	MXRH	Maximum Relative Humidity
23	PRCP	Daily Precipitation
24	PRES	Average Daily Station Pressure
26	RDIR	Resultant Wind Direction
27	RWND	Resultant Wind Speed
30	SCSS	Average Sky Cover Sunrise to Sunset
31	SLVP	Average Daily Sea Level Pressure
36	TMAX	Daily Maximum Temperature
37	TMIN	Daily Minimum Temperature
38	TMPW	Average Daily Wet-Bulb Temperature
39	TOBS	Temperature at Observation Time
40	TSUN	Daily Total Sunshine, expressed in minutes

TABLE 4.2
SUBSET OF WEATHER STATION SITES INCLUDED IN EPA MODEL INPUT DATA FILES

Station Index	Station Name
1	ASTORIA REGIONAL AIRPORT
2	BEULAH
3	BOISE AIR TERMINAL
4	CASCADE 1 NW
5	EUGENE MAHLON SWEET ARPT
6	FENN RANGER STATION
7	GOODING 2 S
8	LA GRANDE
9	LEADORE NO 2
10	LEWISTON NEZ PERCE CNTY AP
11	MEDFORD ROGUE VALLEY INTL AP
12	OLYMPIA AIRPORT
13	POCATELLO REGIONAL AP
14	PORTLAND INTERNATIONAL AP
15	QUILLAYUTE STATE AIRPORT
16	RICHLAND
17	SALEM MCNARY FIELD
18	SEATTLE-TACOMA INTL AP
19	SPOKANE INTERNATIONAL AP
21	TETONIA EXPERIMENT STN
22	WENATCHEE
23	WENATCHEE EXP STN
24	WENATCHEE PANGBORN FIELD
25	YAKIMA AIR TERMINAL

From the extracted data sets for the above stations and parameters, we generated a pair of tables to display the number of measurements extracted (Table 4.3), and the period(s) of record (Table 4.4). This quantifies the extent of the measurement battery for each measured value at each station. By doing this, we could examine the spatial and temporal extent of key variables needed for the model meteorological data input. From either table, it is evident that the basis of the model is a patch quilt of data sewn together. There are significant gaps in both the temporal and spatial data record. Although some stations (e.g., Yakima and Spokane) are well populated, especially in the post 1984 years. Many stations, such as Richland, Beulah, Fenn, and Gooding, only monitor precipitation and air temperature; they have limited or non-existent coverage of other key measurement battery variables.

The measurements of primary importance for the EPA model are relative humidity (or their surrogates: dew point and wet bulb temperature), cloud cover (or directly measured radiation data from BuRec AgriMet stations or other sources), wind speed, and air temperature. From this analysis, it is apparent that the NCDC dataset we analyzed spans the range from 1975 through 1995 for minimum and maximum air temperature and for cloud cover, but not for other key variables needed for the water surface heat exchange equations: relative humidity (or the surrogates wet bulb and dew point temperature) or wind speed. For the later group, the period of record did not start until 1984. We are still uncertain as to the original source from which the EPA obtained the data used to span the period from 1975 to 1984, or if physical measurements were actually used. From the analysis above, it is clear why the EPA opted to employ correlation between stations: they use correlation to justify using only a handful of the numerous sites they list as input files in the model. Only a small percentage of the sites had sufficient data to supply essential input parameters to the model. We presume the remaining are synthetic data.

TABLE 4.3
NUMER OF MEASUREMENTS ACTUALLY RESIDING IN EACH VARIABLE AND EACH WEATHER STATION FILE CONTAINED IN THE EPA MODEL INPUT FILES
(Note the extensive variability)

Data Counts for Indicated Parameters at Indicated Stations.

	station index	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	21	22	23	24	25
Element Index	Element Name	ASTORIA REGIONAL AIRPORT	BEULAH	BOISE AIR TERMINAL	CASCADE 1 NW	EUGENE MAHLON SWEET ARPT	FENN RANGER STATION	GOODING 2 S	LA GRANDE	LEADORE NO 2	LEWISTON NEZ PERCE CNTY AP	MEDFORD ROGUE VALLEY INTL AP	OLYMPIA AIRPORT	POCATELLO REGIONAL AP	PORTLAND INTERNATIONAL AP	QUILLAYUTE STATE AIRPORT	RICHLAND	SALEM MCNARY FIELD	SEATTLE SEATTLE-TACOMA INTL AP	SPOKANE INTERNATIONAL AP	TETONIA EXPERIMENT STN	WENATCHEE	WENATCHEE EXP STN	WENATCHEE PANGBORN FIELD	YAKIMA AIR TERMINAL
2	**Daily Wind Speed**	6536	0	6544	0	6544	0	0	0	0	6419	6544	6538	6544	6544	6544	0	6544	6542	6543	0	0	0	395	6544
5	**Average Daily Dew Point Temp**	6519	0	6542	0	6525	0	0	0	0	6397	6539	6478	6539	6533	6521	0	6498	6542	6518	0	0	0	390	6519
9	Daily Evaporation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3027	0	0	2977	0	3281
16	Daily Min Temp of Water in Evap Pan	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3071	0	0	2912	0	3236
17	Minimum Relative Humidity	6450	0	6454	0	6454	0	0	0	0	6329	6454	6451	6454	6454	6450	0	6453	6452	6454	0	0	0	1156	6453
18	**Average Air Temperature**	6544	0	6544	0	6543	0	0	0	0	6537	6544	6535	6544	6544	6542	0	6544	6543	6544	0	0	0	6513	6544
19	Daily Max Temp of Water in Evap Pan	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3071	0	0	2910	0	3236
20	Maximum Relative Humidity	6448	0	6454	0	6454	0	0	0	0	6329	6454	6451	6454	6454	6450	0	6453	6452	6454	0	0	0	1156	6452
23	Daily Precipitation	9109	9269	9833	9790	9814	9631	4141	9806	5103	9769	9861	9740	9832	9774	9860	9455	9757	9861	9716	9174	9814	8238	9860	9830
24	Average Daily Station Pressure	6535	0	6543	0	6539	0	0	0	0	6413	6541	6532	6539	6538	6533	0	6537	6542	6520	0	0	0	393	6540
26	Resultant Wind Direction	6528	0	6542	0	6540	0	0	0	0	6410	6541	6537	6543	6544	6538	0	6537	6542	6544	0	0	0	392	6537
27	Resultant Wind Speed	6528	0	6542	0	6540	0	0	0	0	6410	6541	6537	6543	6544	6538	0	6537	6542	6544	0	0	0	392	6537
30	**Average Sky Cover (Sunrise to Sunset)**	6558	0	7540	0	7449	0	0	0	0	4753	8299	7419	7630	7509	7904	0	7386	7843	7448	0	0	0	0	7660
31	Average Daily Sea Level Pressure	6534	0	6538	0	6513	0	0	0	0	6391	6537	6497	6532	6531	6522	0	6525	6541	6532	0	0	0	390	6517
36	Daily Maximum Temperature	9861	9061	9858	9795	9861	9575	4221	9814	4673	9851	9859	9851	9856	9857	9859	9503	9859	9858	9832	8402	9815	8246	9851	9859
37	Daily Minimum Temperature	9806	9021	9848	9793	9764	9508	4227	9776	4574	9846	9861	9810	9828	9847	9859	9501	9841	9860	9815	8299	9809	8245	9860	9848
38	**Average Daily Wet Bulb Temperature**	6519	0	6542	0	6525	0	0	0	0	6396	6539	6478	6539	6533	6521	0	6498	6542	6518	0	0	0	390	6519
40	Daily Total Sunshine (expressed in minutes)	3	0	9794	0	3	0	0	0	0	0	3	1	9812	7609	7844	0	0	7865	7604	0	0	0	0	1

Color codes are as follows: red = , blue = , purple = , black =

TABLE 4.4
A SYNOPSIS OF THE TEMPORAL DISCONTINUITY OF THE MEASUREMENT BATTERY USED IN THE EPA MODEL
(Color codes per Table 4.3)

Period of Record for Indicated Parameters at Indicated Stations.

Element Index	station index / Element Name	1 ASTORIA REGIONAL AIRPORT	2 BEULAH	3 BOISE AIR TERMINAL	4 CASCADE 1 NW	5 EUGENE MAHLON SWEET ARPT	6 FENN RANGER STATION	7 GOODING 2 S	8 LA GRANDE	9 LEADORE NO 2	10 LEWISTON NEZ PERCE CNTY AP	11 MEDFORD ROGUE VALLEY INTL AP	12 OLYMPIA AIRPORT
7	Daily Wind Speed	1/84 - 12/01	no data	1/84 - 12/01	0	1/84 - 12/01	no data	no data	no data	no data	1/84 - 12/01	1/84 - 12/01	1/84 - 12/01
5	Average Daily Dew Point Temp	1/84 - 12/01	0	1/84 - 12/01	0	1/84 - 12/01	no data	no data	no data	no data	1/84 - 12/01	1/84 - 12/01	1/84 - 12/01
9	Daily Evaporation	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data
16	Daily Min Temp of Water in Evap Pan	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data
17	Minimum Relative Humidity	1/84 - 12/01	no data	1/84 - 12/01	no data	1/84 - 12/01	no data	no data	no data	no data	1/84 - 12/01	1/84 - 12/01	1/84 - 12/01
18	Average Air Temperature	1/84 - 12/01	no data	1/84 - 12/01	no data	1/84 - 12/01	no data	no data	no data	no data	1/84 - 12/01	1/84 - 12/01	1/84 - 12/01
19	Daily Max Temp of Water in Evap Pan	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data
20	Maximum Relative Humidity	1/84 - 12/01	no data	1/84 - 12/01	no data	1/84 - 12/01	no data	no data	no data	no data	1/84 - 12/01	1/84 - 12/01	1/84 - 12/01
23	Daily Precipitation	1/75 - 12/01	1/75 - 12/01	1/75 - 12/01	1/75 - 12/01	1/75 - 12/01	1/75 - 12/01	7/76 - 4/81 5/87 - 10/88 8/89 - 7/90 10/92 - 2/97	1/75 - 12/01	1/75 - 10/84 2/88 - 3/89 7/96 - 12/01	1/75 - 12/01	1/75 - 12/01	1/75 - 12/01
24	Average Daily Station Pressure	1/84 - 12/01	no data	1/84 - 12/01	no data	1/84 - 12/01	no data	no data	no data	no data	1/84 - 12/01	1/84 - 12/01	1/84 - 12/01
26	Resultant Wind Direction	1/84 - 12/01	no data	1/84 - 12/01	no data	1/84 - 12/01	no data	no data	no data	no data	1/84 - 12/01	1/84 - 12/01	1/84 - 12/01
27	Resultant Wind Speed	1/84 - 12/01	no data	1/84 - 12/01	no data	1/84 - 12/01	no data	no data	no data	no data	1/84 - 12/01	1/84 - 12/01	1/84 - 12/01
30	Average Sky Cover (Sunrise to Sunset)	1/75 - 2/93	no data	1/75 - 11/95	no data	1/75 - 8/95	no data	no data	no data	no data	1/75 - 2/89	1/75 - 12/97	1/75 - 10/95
31	Average Daily Sea Level Pressure	1/84 - 12/01	no data	1/84 - 12/01	no data	1/84 - 12/01	no data	no data	no data	no data	1/84 - 12/01	1/84 - 12/01	1/84 - 12/01
36	Daily Maximum Temperature	1/75 - 12/01	1/75 - 12/01	1/75 - 12/01	1/75 - 12/01	1/75 - 12/01	1/75 - 12/01	7/76 - 4/81 5/87 - 7/90 4/92 - 9/97	1/75 - 12/01	1/75 - 11/84 2/88 - 3/89 7/96 - 12/01	1/75 - 12/01	1/75 - 12/01	1/75 - 12/01
37	Daily Minimum Temperature	1/75 - 12/01	1/75 - 12/01	1/75 - 12/01	1/75 - 12/01	1/75 - 12/01	1/75 - 12/01	7/76 - 4/81 5/87 - 7/90 4/92 - 9/97	1/75 - 12/01	1/75 - 11/84 2/88 - 3/89 7/96 - 12/01	1/75 - 12/01	1/75 - 12/01	1/75 - 12/01
38	Average Daily Wet Bulb Temperature	1/84 - 12/01	no data	1/84 - 12/01	no data	1/84 - 12/01	no data	no data	no data	no data	1/84 - 12/01	1/84 - 12/01	1/84 - 12/01
40	Daily Total Sunshine (expressed in minutes)	no data	no data	1/75 - 12/31	no data	1/75 - 12/31	no data	no data	no data	no data	no data	no data	no data

Element Index	station index / Element Name	13 POCATELLO REGIONAL AP	14 PORTLAND INTERNATIONAL AP	15 QUILLAYUTE STATE AIRPORT	16 RICHLAND	17 SALEM MCNARY FIELD	18 SEATTLE-TACOMA INTL AP	19 SPOKANE INTERNATIONAL AP	21 TETONIA EXPERIMENT STN	22 WENATCHEE	23 WENATCHEE EXP STN	24 WENATCHEE PANGBORN FIELD	25 YAKIMA AIR TERMINAL
7	Daily Wind Speed	1/84 - 12/01	1/84 - 12/01	1/84 - 12/01	no data	1/84 - 12/01	1/84 - 12/01	1/84 - 12/01	no data	no data	no data	11/00 - 12/01	1/84 - 12/01
5	Average Daily Dew Point Temp	1/84 - 12/01	1/84 - 12/01	1/84 - 12/01	no data	1/84 - 12/01	1/84 - 12/01	1/84 - 12/01	no data	no data	no data	11/00 - 12/01	1/84 - 12/01
9	Daily Evaporation	no data	no data	no data	no data	no data	no data	4/79 - 5/96	no data	no data	4/79 - 9/97	no data	9/79 - 9/97
16	Daily Min Temp of Water in Evap Pan	no data	no data	no data	no data	no data	no data	4/79 - 5/96	no data	no data	4/79 - 9/84, 6/97 - 9/97	no data	9/79 - 9/97
17	Minimum Relative Humidity	1/84 - 12/01	1/84 - 12/01	1/84 - 12/01	no data	1/84 - 12/01	1/84 - 12/01	1/84 - 12/01	no data	no data	no data	4/97 - 12/01	1/84 - 12/01
18	Average Air Temperature	1/84 - 12/01	1/84 - 12/01	1/84 - 12/01	no data	1/84 - 12/01	1/84 - 12/01	1/84 - 12/01	no data	no data	no data	1/84 - 12/01	1/84 - 12/01
19	Daily Max Temp of Water in Evap Pan	no data	no data	no data	no data	no data	no data	4/79 - 5/96	no data	no data	4/79 - 9/97	no data	9/79 - 9/97
20	Maximum Relative Humidity	1/84 - 12/01	1/84 - 12/01	1/84 - 12/01	no data	1/84 - 12/01	1/84 - 12/01	1/84 - 12/01	no data	no data	no data	4/97 - 12/01	1/84 - 12/01
23	Daily Precipitation	1/75 - 12/01	1/75 - 12/01	1/75 - 12/01	1/75 - 12/01	1/75 - 12/01	1/75 - 12/01	1/75 - 12/01	1/75 - 12/01	1/75 - 12/01	1/75 - 9/97	1/75 - 12/01	1/75 - 12/01
24	Average Daily Station Pressure	1/84 - 12/01	1/84 - 12/01	1/84 - 12/01	no data	1/84 - 12/01	1/84 - 12/01	1/84 - 12/01	no data	no data	no data	11/00 - 12/01	1/84 - 12/01
26	Resultant Wind Direction	1/84 - 12/01	1/84 - 12/01	1/84 - 12/01	no data	1/84 - 12/01	1/84 - 12/01	1/84 - 12/01	no data	no data	no data	11/00 - 12/01	1/84 - 12/01
27	Resultant Wind Speed	1/84 - 12/01	1/84 - 12/01	1/84 - 12/01	no data	1/84 - 12/01	1/84 - 12/01	1/84 - 12/01	no data	no data	no data	11/00 - 12/01	1/84 - 12/01
30	Average Sky Cover (Sunrise to Sunset)	1/75 - 2/96	1/75 - 10/95	1/75 - 11/96	no data	1/75 - 6/96	1/75 - 9/96	1/75 - 8/95	no data	no data	no data	no data	1/75 - 3/96
31	Average Daily Sea Level Pressure	1/84 - 12/01	1/84 - 12/01	1/84 - 12/01	no data	1/84 - 12/01	1/84 - 12/01	1/84 - 12/01	no data	no data	no data	11/00 - 12/01	1/84 - 12/01
36	Daily Maximum Temperature	1/75 - 12/01	1/75 - 12/01	1/75 - 12/01	1/75 - 12/01	1/75 - 12/01	1/75 - 12/01	1/75 - 12/01	1/75 - 12/01	1/75 - 12/01	1/75 - 9/97	1/75 - 12/01	1/75 - 12/01
37	Daily Minimum Temperature	1/75 - 12/01	1/75 - 12/01	1/75 - 12/01	1/75 - 12/01	1/75 - 12/01	1/75 - 12/01	1/75 - 12/01	1/75 - 12/01	1/75 - 12/01	1/75 - 9/97	1/75 - 12/01	1/75 - 12/01
38	Average Daily Wet Bulb Temperature	1/84 - 12/01	1/84 - 12/01	1/84 - 12/01	no data	1/84 - 12/01	1/84 - 12/01	1/84 - 12/01	no data	no data	no data	11/00 - 12/01	1/84 - 12/01
40	Daily Total Sunshine (expressed in minutes)	1/75 - 12/31	1/75 - 10/95	1/75 - 9/96	no data	no data	1/75 - 9/96	1/75 - 2/99	no data	no data	no data	no data	no data

We examined other data sets including the AgriMet database collected by the USBR. We found that data relevant to the input set required by the EPA model are also available for more recent years. None of the AgriMet data we examined spanned as far back as 1975. Table 4.4 shows the available periods of record for each AgriMet station examined in the Pacific Northwest.

With the exception of Yakima and Lewiston, most of the well populated NCDC data sets are either located at relatively long distances from the main stem of the Snake and Columbia rivers (e.g., Medford, Oregon), or tended to be congregated toward the outside ends of the system (for example Seattle, Portland, Astoria, and Spokane). Collectively, the well-populated stations provide a relatively small number of locations with a solid temporal data set across the entire measurement battery. In short, very few stations exist with contemporaneous data across all measurement variables. Those that do are often quite distant from the river. It was from these stations that EPA extrapolated data for input files that had incomplete data histories or incomplete measurement batteries, or both.

4.3 Comparison of EPA Input Data to Direct Measurements

The USBR operates a series of meteorological monitoring stations for agricultural purposes (AgriMet) throughout the United States. These AgriMet stations monitor a range of parameters including wind speed, relative humidity, air temperature, solar radiation and others. As part of the review of the EPA modeling effort, data from USBR stations that are relatively close to specific EPA stations (Table 4.5) were analyzed and compared to data contained in the EPA input files (referred to as *.hot files) in the EPA report. Table 4.6 shows a list of AgriMet stations in the Pacific Northwest, with those that were examined for this exercise shown in bold font. Figure 1 shows a map of area AgriMet stations (depicted as named filled circles) as well as the EPA hot file locations (shown as numbered squares). Names corresponding to EPA input file numbers shown in the map on Figure 4.1 are defined in Table 4.5.

In reviewing the data contained in the various EPA input files, a number of details emerged. First, it is clear that data from certain files were sometimes used in more than one place to create the dataset used for the EPA input files. For example, the wind speed and vapor pressure values contained in the Wenatchee model input data file are identical to those contained in the Richland model input data files. The air temperatures for those two sets, however, are not identical. This created some physically impossible contradictions within the input files used to supply input data to the model. For example, the Wenatchee input file contains situations where a dry bulb temperature is reported along with a corresponding vapor pressure value that exceeds the theoretical maximum saturation vapor pressure for the given temperature. This physically impossible condition is represented in approximately 5 percent of the readings supplied for the Wenatchee input vapor pressure values (412 times out of 7,664 points). Among the ramifications that this condition leads to is the fact that the calculated relative humidity values exceed 100 percent, and since convection rates are computationally linked to evaporation rates in the model formulations, the evaporation rate would either halt or even could reverse direction (supplying additional heating rather than a cooling effect). If data are substituted from one station to another, they must be carefully screened to ensure that physically impossible conditions are not accidentally represented, as happened in this case.

TABLE 4.5
LIST OF AGRIMET STATIONS IN THE PACIFIC NORTHWEST CORRESPONDING TO AND USED TO CORROBORATE EPA INPUT MODEL SOURCE DATA

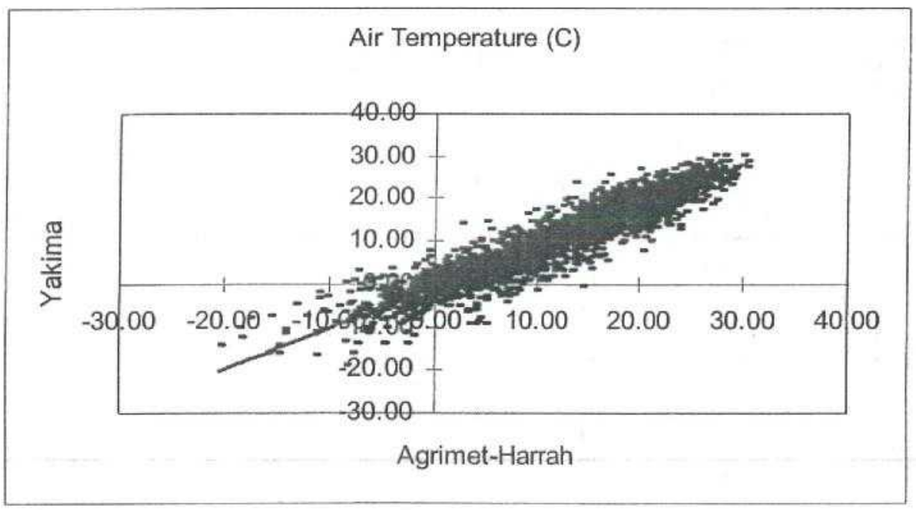
Hot File Map Number	Hot File Name
1	Alleghany
4	Astoria WSO Airport
5	Beulah
6	Boise WSFO Airport
7	Calder
8	Cascade 1 NW
10	Cougar 4 SW
11	Eugene WSO Airport
13	Fenn Ranger Station
14	Frances
15	Gooding 1 S
16	Grasmere 3 S
18	LaGrande
19	Leadore
20	Lewiston Nez Perce County Airport
21	Marblemount Ranger Station
23	Medord WSO Airport
24	Ochoco Dam
25	Olympia Airport
26	Pendleton WSO Airport
27	Pocatello WSO Airport
28	Portland International Airport
29	Quillayute WSCMO Airport
30	Richland
31	Salem WSO Airport
32	Sandpoint Experiment Station
33	Seattle Tacoma International Airport
34	Snoqualmie Pass
35	Spokane WSO Airport
37	Tetonia Experiment Station
38	Whitman Mission
39	Wenatchee
40	Yakima WSO Airport

TABLE 4.6
AGRIMET STATIONS (BOLD) THAT WERE COMPARED WITH EPA INPUT DATA FOR RELIABILITY

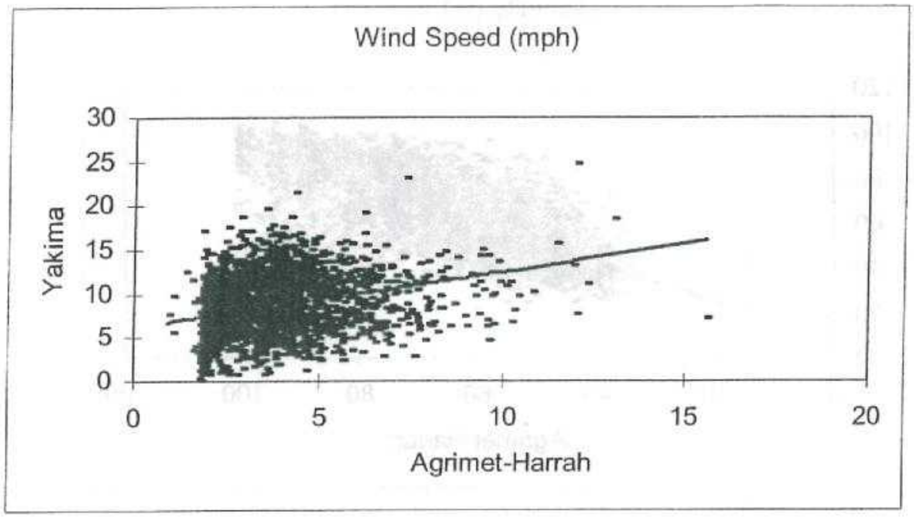
				Latitude			Longitude			
StationID	**StationName**	**State**	**Elevation**	**deg**	**min**	**sec**	**deg**	**min**	**sec**	**install date**
ABEI	Aberdeen	ID	4400	42	57	12	112	49	36	3/20/91
AFTY	Afton	WY	6210	42	44	00	110	56	09	10/20/87
AHTI	Ashton	ID	5300	44	01	30	111	28	00	6/2/87
ARAO	Aurora	OR	140	45	16	55	122	45	01	10/22/98
BANO	Bandon	OR	80	43	05	28	124	25	02	5/15/85
BKVO	Baker Valley	OR	3420	44	52	55	117	57	49	5/11/01
BOII	Boise	ID	2720	43	37	15	116	11	10	7/31/95
BRKO	Brookings	OR	80	42	01	48	124	14	27	9/28/99
CEDC	Cedarville	CA	4600	41	35	07	120	10	17	4/24/85
CHVO	Christmas Valley	OR	4360	43	14	29	120	43	41	4/22/85
COVM	Corvallis	MT	3597	46	20	00	114	05	00	4/27/84
CRSM	Creston	MT	2950	48	11	15	114	07	40	5/4/88
CRVO	Corvallis	OR	230	44	38	03	123	11	24	2/27/90
DEFO	**Dee Flat**	OR	1260	45	34	25	121	38	50	2/21/90
DRLM	Deer Lodge	MT	4680	46	20	08	112	46	00	6/4/98
ECHO	Echo	OR	760	45	42	40	119	21	00	3/24/88
EURN	Eureka	NV	5897	39	41	07	115	58	43	8/8/01
FAFI	Fairfield	ID	5038	43	18	30	114	49	30	6/25/87
FALN	Fallon	NV	3965	39	27	29	118	46	37	3/27/01
FOGO	**Forest Grove**	OR	180	45	33	11	123	05	01	8/29/91
FTHI	Fort Hall	ID	4445	43	04	17	112	25	52	4/2/93
GDVI	Grand View	ID	2580	42	54	45	116	03	22	2/10/93
GERW	**George**	WA	1150	47	02	38	119	38	32	5/15/86
GFRI	Glenns Ferry	ID	3025	42	52	00	115	21	25	4/13/93
GOLW	**Goldendale**	WA	1680	45	48	43	120	49	28	11/27/91
HERO	**Hermiston**	OR	550	45	49	16	119	30	44	5/17/83
HOXO	**Hood River**	OR	510	45	41	04	121	31	05	5/19/87
HRFO	**Hereford**	OR	3600	44	29	17	118	01	12	4/29/98
HRHW	**Harrah**	WA	850	46	23	05	120	34	28	5/27/87
HRMO	**Hermiston (Harec)**	OR	607	45	49	10	119	17	00	7/15/93
IMBO	Imbler	OR	2750	45	26	00	117	58	00	4/5/94
KFLO	Klamath Falls	OR	4100	42	09	53	121	45	18	3/31/99
KTBI	Kettle Butte	ID	5135	43	32	55	112	19	33	10/1/96
LAKO	Lakeview	OR	4770	42	07	20	120	31	23	4/19/88
LEGW	**Legrow**	WA	580	46	12	19	118	56	10	7/17/86
LIDW	**Lind**	WA	1475	46	52	02	118	44	22	5/18/83
LORO	Lorella	OR	4160	42	04	40	121	13	27	3/31/01
MALI	Malta	ID	4410	42	26	15	113	24	50	6/2/83
MASW	**Manson**	WA	1972	47	55	01	120	07	28	11/9/93
MDFO	**Medford**	OR	1340	42	19	52	122	56	16	5/23/89
MNTI	Monteview	ID	4855	44	00	54	112	32	09	10/1/96
MRSO	Madras	OR	2440	44	40	48	121	08	55	5/2/84
NMPI	Nampa	ID	2634	43	26	30	116	38	13	3/11/96
ODSW	**Odessa**	WA	1650	47	18	32	118	52	43	4/24/84
OMAW	**Omak**	WA	1235	48	24	09	119	34	34	1/25/89
ONTO	Ontario	OR	2260	43	58	40	117	00	55	4/30/92
PARO	**Parkdale**	OR	1480	45	32	40	121	37	00	10/20/89
PCYO	Prairie City	OR	3752	44	26	27	118	37	40	4/12/89
PICI	Picabo	ID	4900	43	18	42	114	09	57	4/21/93
PMAI	Parma	ID	2305	43	48	00	116	56	00	3/28/86
PNGO	**Pinegrove**	OR	620	45	39	00	121	30	20	10/20/89
POBO	Powell Butte	OR	3200	44	14	54	120	56	59	9/21/93
RDBM	Round Butte	MT	3040	47	32	22	114	16	50	5/23/89
RPTI	Rupert	ID	4155	42	35	42	113	50	17	3/9/88
RXGI	Rexburg	ID	4875	43	51	00	111	46	00	6/3/87
SIGM	St.Ignatius	MT	2940	47	18	48	114	05	53	3/28/91
TWFI	Twin Falls (Kimberly)	ID	3920	42	32	46	114	20	43	5/4/90
WRDO	Worden	OR	4080	42	01	01	121	47	13	4/19/00

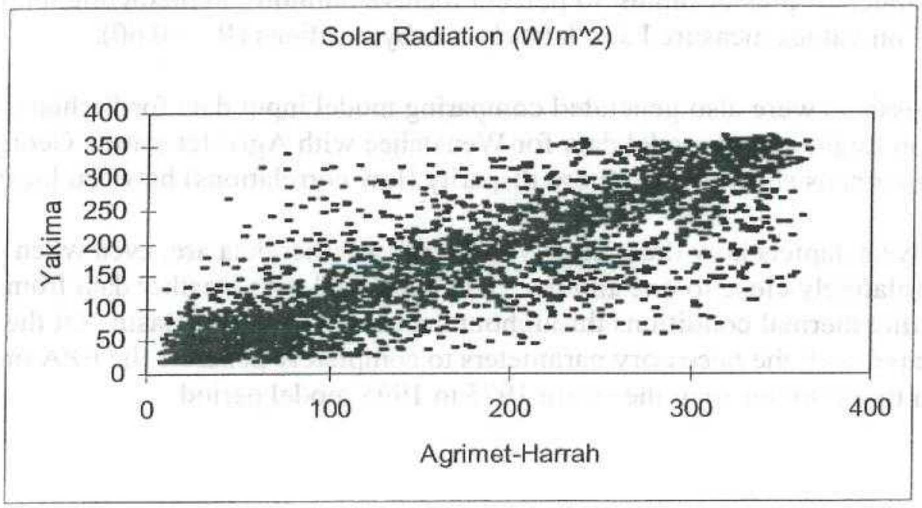
We then systematically compared nearby AgriMet sites to three of the four main EPA meteorological input data source files to assess the accuracy of the input data (Lewiston, Richland, Wenatchee, and Yakima). Lewiston is not in close proximity to any AgriMet stations so it was not included in this exercise. It should be noted that one very important parameter (longwave atmospheric radiation) was never directly measured at any site we were able to identify. (For the EPA model, longwave radiation is the primary driver of energy input into the river. We discuss the significance of not measuring longwave atmospheric radiation in the next section of this report.)

For the three remaining EPA input file stations and their AgriMet counterparts, a series of correlation analyses were performed. Data of the same variable collected at the exact same time were paired between the input variables and the AgriMet stations. These analyses reveal the limited extent to which one data set (the EPA input file) possesses the predictive ability to represent its measured counterpart (the AgriMet station file data). Such an analysis prompts the question that if these correlations are poor, how much worse would the correlations be within river reaches that are a much greater distance away? The analyses also characterize the accuracy and the level of variability of the data. The following charts show the correlation between the EPA input file values, and those reported by the closest AgriMet station for the period of useful record for the AgriMet station. The temperature data resulted in a close fit between stations; the following plot compares model data for Yakima with the AgriMet station at Harrah, along with a regression line (mostly hidden by the data):

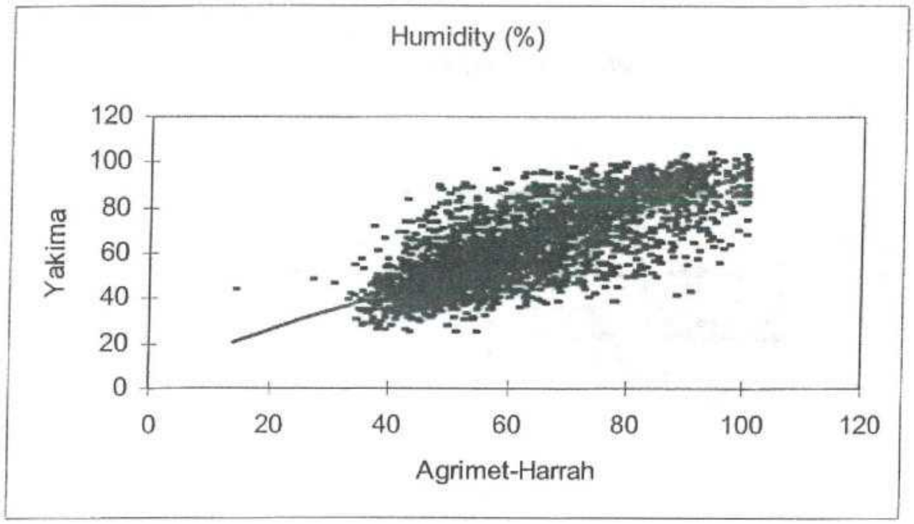


In spite of a relatively good fit ($R^2 = 0.88$), the predictive ability is low. That is, if one station were to be used to estimate temperature at the other station, there would be an error of up to plus or minus 10°C. For other model input parameters, the fit against real data was worse to nonexistent.





The assumption that nearby stations have similar weather does not hold true for wind speed and solar radiation ($R^2 = 0.09$ and 0.70, respectively). This does not even address the fact that wind speed over water is significantly higher than wind speed over land (see previous section on Review of the Model). In many cases both AgriMet and NCDC Stations are not immediately adjacent to the river or reach of concern.



Humidity, also upon casual inspection, seems somewhat similar between locations. However, the error is as much as plus or minus 30 percent relative humidity in predicting humidity at one location based on values measured at relatively nearby locations ($R^2 = 0.60$).

Plots and regressions were also generated comparing model input data for Richland with nearby AgriMet station Legrow, and model data for Wenatchee with AgriMet station George. These and other comparisons showed even more disparity (low correlations) between locations.

This brief analysis depicts how dramatically disparate weather data are, even when collected from stations relatively close to one another. Yet the model uses weather data from only four stations to predict thermal conditions throughout the entire Columbia Basin. Of the four, only two are populated with the necessary parameters to completely generate the EPA model input files, and even those do not span the entire 1975 to 1995 model period.

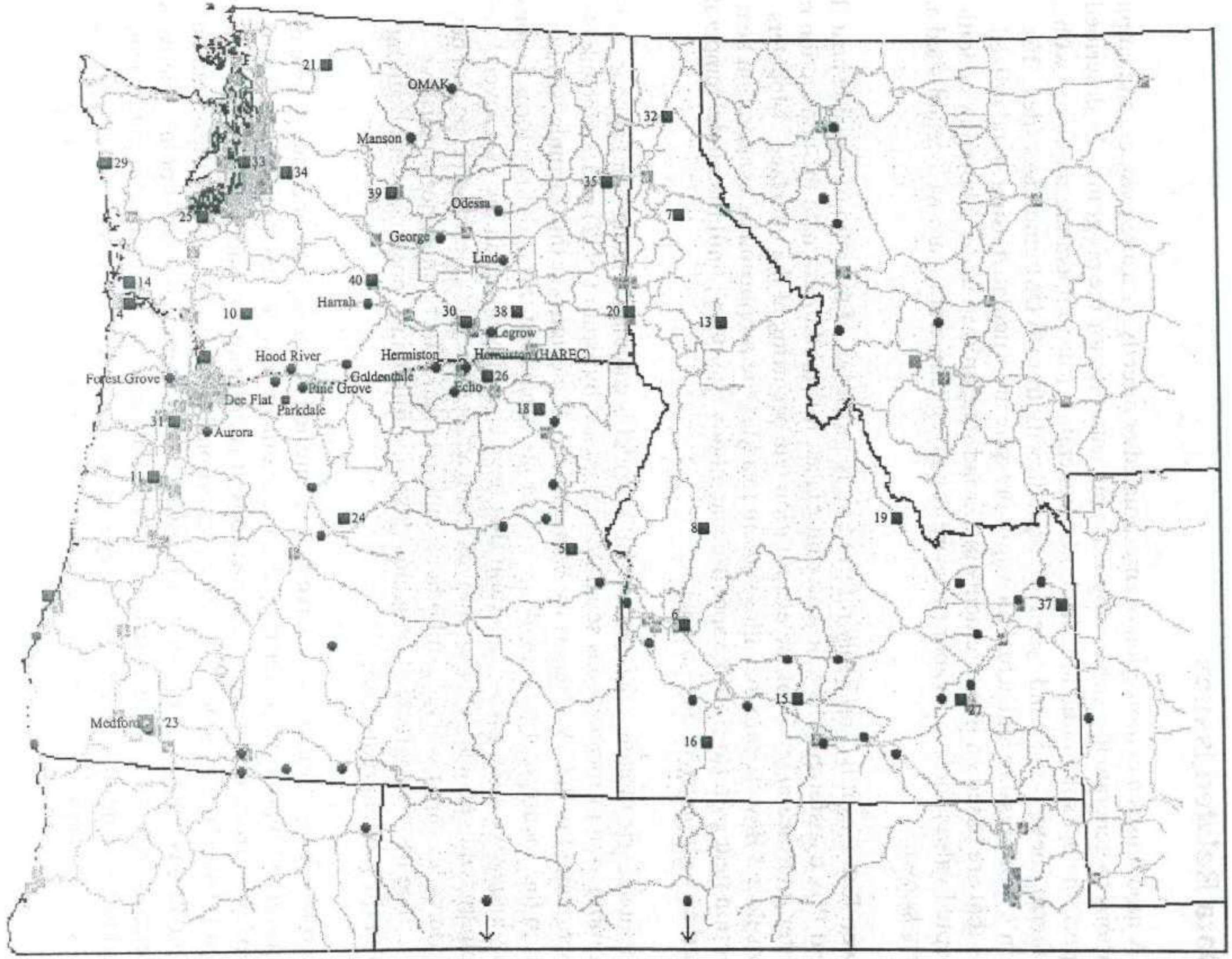


Figure 4.1 – Map of NCDC Meteorological Stations and USBR AgriMet Stations in the Pacific Northwest

Section 5 - Issues with Predictive Formulas to Estimate Model Input Parameters

5.1 Data Related Issues

The EPA model uses a combination of interpolated or directly measured values, and empirical formulations to generate the meteorological input data files for the program. As described in the EPA report, the net solar radiation, dry bulb temperature (the temperature measured with a regular thermometer), and wind speed are read directly from WDM input data files. The saturation vapor pressure and actual air vapor pressure are calculated using standardized formulas that are based on measurements made and standardized under laboratory conditions. The accepted values for water vapor pressure at a given temperature are well established and accurately known.

The Bowen Ratio, as it is commonly referred to, is a measure of the ratio of sensible heat flux to latent heat flux transferred at the air water interface. It is used to estimate the convection rate at an air water interface in terms of the evaporation rate occurring at the interface. Modelers typically select a Bowen ratio that allows them to adjust the proportion of evaporation heat loss to convection heat gain (to fit some specific water body geometry) until the model temperature output agrees with physical measurements.

The net atmospheric radiation data for the EPA model is calculated using what appears to be a hybrid combination of formulations separately proposed by Brunt (1932) and Swinbank (1963) and is documented in the TVA report by Wunderlich. The origin for this formula was not described in the documentation provided. Numerous variants of this and other formulations for estimating longwave atmospheric radiation flux have been developed in the past several decades. More sophisticated versions have tried to take into account the altitude, cloud type and height, atmospheric water vapor content, and other conditions that effect atmospheric emissive properties. The EPA's approach as it stands raises the following concerns over obtaining precision in the model predictiveness:

Because no longwave radiation data have been identified to confirm the accuracy of the results, they are currently impossible to verify. Although in many models, the longwave radiation is "estimated" by surrogate variables and equations, it is the primary source of thermal input. The level of confidence in the model is directly proportional to ability to validate the amount of error in the formulations used to construct it. Longwave atmospheric radiation supplies relatively high levels of energy input to the water surface, so errors made in the approximation of its value would lead to more significant error in the estimation of net water surface heat flux than would errors made in the approximation of other energy flux terms (convection for example).

A comparison of the model input values for daily average longwave atmospheric radiation versus daily averaged short wave solar radiation is shown on Figure 5.1. This chart shows that for most of the year, the daily average rates for longwave radiation flux exceed the net level for short wave radiation.

5.2 Heat Transfer (Model) Issues: Thermal and Hydraulic

There are two primary issues relating to the extrapolation of "transfer mechanisms": thermal and hydraulic/geometric.

Coefficients based on calibration of a base (reservoir) condition should not be used as the same set of coefficients to predict the behavior under extrapolated (river) conditions as they are not equivalent comparisons. Evaporation, convection, and back radiation rates are functions of the surface water temperature and/or the atmospheric conditions. As applied by EPA, they may not hold true if the conditions are changed from the base calibration assumptions for various reasons.

In the case of geometric extrapolations, several additional problems could be encountered that are not validated by the EPA exercise (a difficult task using currently available data). These assumptions are rooted in the basic assumptions used in numerous thermal models and are well documented (cf. Wunderlich, 1972). These assumptions are also the basis of the EPA routines to calculate evaporative and convective heat transfer at the air/water interface, and are widely applied in many other thermal models in use today. These are referred to as latent and sensible heat convection, respectively, in the report. They are component parts of Bowen's Ratio and affect the model's ability to estimate heat transfer.

5.3 Bowen's Ratio and Evaporation Assumptions

At the foundation of this approach is an assumption that a thin boundary layer of air develops at the air water interface that is cooled to the air wet bulb temperature by the water surface. The extent to which this "equilibrium temperature" is approached in the boundary layer is, among other things, a function of the shape, length, and width of the water surface being modeled, and of the prevailing psychrometric conditions. The analyst obtains an evaporation coefficient to produce an evaporation rate formula that is generally a function of vapor pressure difference (itself a function of air temperature, water temperature, and relative humidity) , wind speed, and sometimes the barometric pressure. Simultaneously, the modeler manipulates a second coefficient to adjust the proportion of sensible heat transfer (convection) relative to latent heat transfer (evaporative cooling) occurring over the water body. The EPA model accomplishes this second task through the use of a "Bowen Factor" that assigns the relative strength of the latent heat flux rate relative to the sensible heat flux rate. The modeler then manipulates the Bowen Factor and the evaporation coefficient values as functions of wind speed, relative humidity, barometric pressure, and air and water temperatures, until calibration is achieved against an existing water surface geometry under various meteorological conditions.

There are inherent difficulties in this approach in general, and inherent flaws with the way it is applied in the EPA model. First, since the approach relies on existing conditions of water surface temperature and shape, it cannot be accurately extrapolated to estimate properties on a water body of a different temperature and shape (the no dam scenario), because the conditions used to deduce the coefficients are not the same as the simulation conditions. The EPA model uses the same evaporation coefficient and the same Bowen Factor to simulate the no dam condition as it used to calibrate against the with dams scenario. Elements in Wunderlich (*op. cit. p 3.3)* describe the development of a wide range of evaporation formulations in detail.

5.4 Reservoir and River Geometry Differences

Variations in surface area, length, and even wind direction can affect the choice of coefficients selected. This would lead to potentially dramatic discrepancies (and errors) if the surface areas were then radically changed (e.g. substituting a free flowing river in place of a large reservoir). EPA retains the original coefficients for both reservoirs and the assumed river condition. This is a potentially serious flaw because the "shape" of the water body plays a significant role in the determination of the coefficients. Substituting a different "shape" would thereby invalidate the original calibration that is based on reservoir geometry and other conditions.

5.4.1 Stratification: Differences between Reservoirs and Rivers

A second complication of EPA's approach can occur in situations where the reservoirs are strongly stratified, but calibration is achieved against an assumption that the reservoir is thoroughly mixed throughout its volume. This assumption is a necessity of the 1-D Model that EPA has chosen. The method assumes that all energy exchanges occurring at the surface instantly propagate through the entire water column. Within a stratified reservoir during summer months, the surface layer is warmer and tends to radiate, and exchange latent and sensible heat at different (generally higher) rates than it would if the water temperature was representative of a thoroughly mixed impoundment. Measuring the temperature at the turbine discharge where the reservoir temperature is remixed (and presumably averaged) would tend to be lower than the average surface temperature of a stratified reservoir. If this condition is not accounted for, and is used to calibrate the energy exchange formulas, the resulting deduced cooling rates would tend to be over estimated. When the formulas (coefficients) are later applied to a thoroughly mixed river with a lower surface area to volume ratio (no dam scenario), the approach would tend to over estimate the cooling effect taking place at the surface of the river at a given temperature. This would yield a conclusion that the river cooling rates were disproportionately high and that the original reservoir cooling rates were disproportionately low. Such bias would of course exaggerate the beneficial attributes of a natural river (no reservoirs) and underestimate the cooling potential of a reservoir.

A more precise modeling approach would take into account evaporation rates as functions of instantaneous water temperatures, air temperatures, barometric pressures, wind speeds, and relative humidity, such that evaporative, convective and radiation fluxes are calculated locally as functions of the instantaneous local conditions of a specific body of water (river or reservoir each with different geometries and meteorology).

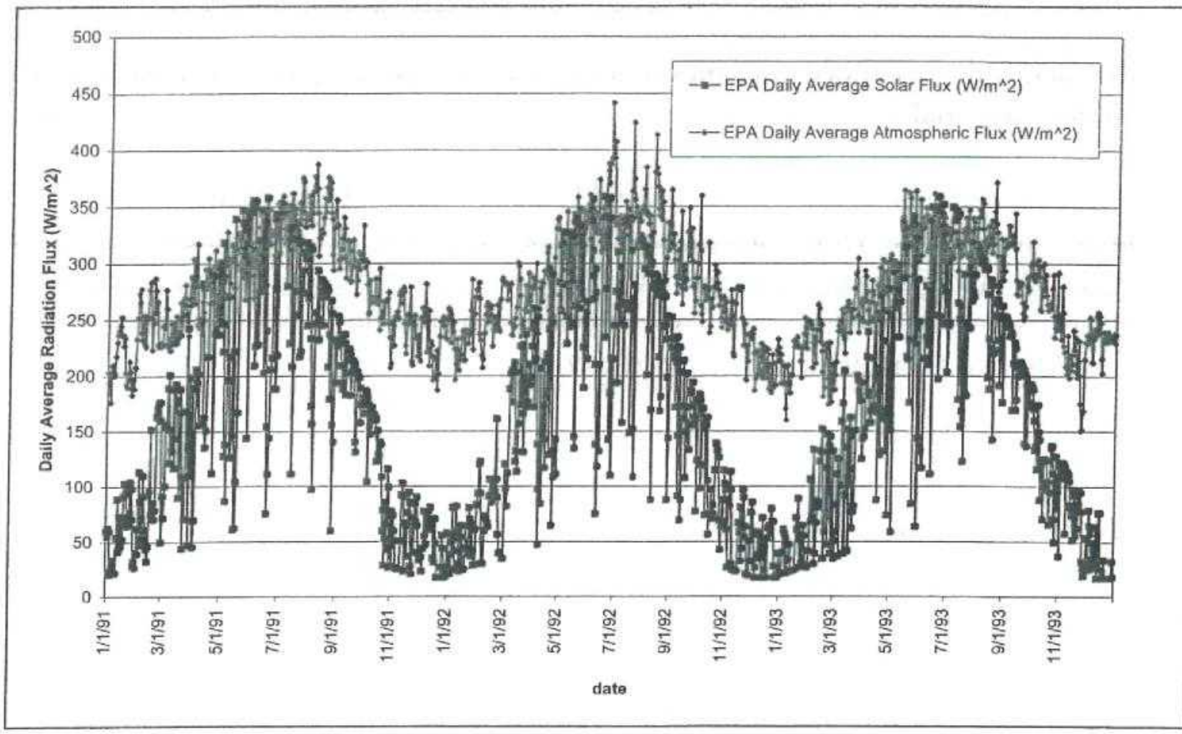


Figure 5.1 – Comparison of Long Wave Atmospheric and Short Wave Solar Radiation Fluxes, Yakima Air Terminal Hot File, 1991-1993

Section 6 - Review of the Magnitude of the Thermal Violations and Criteria

6.1 What Do All These Simulated Temperatures Mean?

The EPA presents a simulation model that the Columbia and Snake Rivers exceed regulatory standards of 18 or 20°C as much as 18 percent of the days in the year. Our review of the EPA model assumptions demonstrates its limitations. The data EPA uses, by our analysis and their own admission is that the magnitude of the problem is of the same magnitude of the potential error or uncertainty in the model.

Even if we were to accept the EPA model, data, and criteria with all its assumptions, what is it telling us?

First, it is telling us that whatever comes into the lower Snake River from the middle Snake River (i.e., Brownlee) in August is coming in warm and would stay warm, with or without the four lower Snake dams. The frequency of violations at Lewiston are about 16 percent where no dams occur and the violations increase 1 to 3 percent at the next four Lower Snake River dams (Figure 3-16, EPA). The changes may not be statistically significant. With all four lower Snake dams removed (EPA simulation), violations decrease from 15 percent to about 14 percent. Thus with the dams gone, there are as many as 14% days in that exceed 20°C but, with the dams in place, there are as many as 18% days of water in excess of 20°C. The biological significance of two to four additional percent of the year of 20.1°C or more is unclear at best. From strictly a physical perspective, this does not seem to be a very effective way to reduce thermal loading from Brownlee to Ice Harbor.

For the Columbia River, the presence (or presumed removal) of Chief Joseph Dam plus the five mid-Columbia dams also seems to make virtually no difference to the thermal regime of the Columbia prior to confluence with the Snake. Priest Rapids, the lowermost dam, shows a violation increase from zero without dam simulation to violations of the 18°C standard in about 2 percent of the time. Remember, an 18.1°C, 19°C, or 20°C change is a violation at Priest Rapids. EPA indicated that only above 20°C does any risk begin to manifest. Examination of data from the early 1990s, some of the driest years on record, show temperatures at Priest Rapids did exceed 18°C but was infrequently and not very greatly above 20°C (Figure 3-5, EPA).

The very large size of both Brownlee and Grand Coulee reservoirs subject them to thermal stratification (see discussion of Froude numbers in Review of the Model Section). Their large mass and residence time delay warming in the spring. Large mass also resists cooling in the fall and extends periods of warm water later into the fall. However, these reservoirs are treated as the "inputs" or boundary to the EPA System Thermal Model by which all subsequent downstream thermal behavior is adjudged. The single most influential element of downstream temperature is the temperature immediately upstream or boundary. In this case, the upstream input is from source reservoirs, Grand Coulee and Brownlee. It may be appropriate to ask whether the input temperatures from these two sources can be improved by either improvements to water management in the upper basins, modification to the intake structures that enable opportunity to use colder hypolimnetic water, or both. This issue is not addressed in the EPA Report even without modeling it. One attribute of a model is realism. Ignoring serious root causes of the thermal behavior of the system limits pragmatic solutions and potential changes or improvements.

Simulated temperatures in the lower Columbia River at McNary, John Day, and Bonneville Dam exceeded the 20°C standard about 12 to 17 percent of the time. It is clear that the warmer temperatures in the Columbia come mainly from the higher temperatures in the Snake (greater than 20°C) mixing (advecting) with the marginal water coming from the mid-Columbia (cf. last sentence, p. 48, EPA). The Snake contributes about one-third of the total discharge of the combined Columbia and Snake Rivers. If the waters coming from Brownlee Dam were significantly cooler, the question would be whether this might lower the thermal regime in the lower Columbia. This was not modeled. However, adjudging from the fact that the lower Snake dams had negligible effect (plus 3 percent violations) coming out of the Hells Canyon reach, it is possible that improvements in the input temperatures from the middle Snake (at the Brownlee control point) might be helpful to the lower Snake. We postulate that a cooler Snake River might subsequently create fewer violations in the lower Columbia and would likely lower average temperatures in the lower Columbia. However, a wellhead of cool water will not emanate from removal of lower Snake River reservoirs when the water is already warm and remains warm as it comes from the upper basin.

Water use and storage in the middle and upper Snake affect water temperature in the lower Snake. To ignore this or take it as a given may ignore a major source of the thermal loading and a potential source of reducing it. Instead, EPA looks at contributions from 12 tributaries that contribute less than 10 percent of the Columbia discharge and concludes that holding these rivers to 16°C does not measurably improve mainstem temperatures. First of all, these tributaries, especially the Yakima, Umatilla, and John Day, are known to violate thermal criteria due to low flows, agricultural use, lack of storage and high thermal loading east of the Cascades. They have affects on salmon that enter those drainages. If these rivers were actually thermally improved, they would reduce the magnitude of thermal loading to the mainstem, something the EPA model is insensitive to. That is because, if cooler tributaries were to lower the mainstem from 22 to 20.1°C, the model would report the same magnitude of "violation." Yet the risk to a salmon at

22°C EPA proffers is higher than one exposed to 20.1°C. Again, this is because the model does not predict instantaneous temperature anywhere in the system. It is incapable of doing that. Instead, it simulates average temperatures and calculates a unit of violation for any simulated average above 20°C. As noted, the model is inapplicable to the regulatory standard of instantaneous violation of standard. To regulate such a standard, one needs far more accurate models and better measurement tools.

6.2 Is Too Much Cold a Good Thing?

The EPA model notes that discharges from only the Clearwater measurably assists thermal conditions in the Snake. Very cold hypolimnetic water from Dworshak Dam advects with the warmer Snake. The differences in temperature may be from 10°C in the Clearwater to 20° or 22°C in the Snake. Although this may seem to be highly beneficial to salmon because it provides local and significant decrease in the thermal environment, the mixing zone is abrupt at the mouth of the Clearwater. Further, the colder water may sink to the bottom of Lower Granite Reservoir rather than mix with the entire river discharge.

Severe changes in temperature, even cooler temperature, can shock fish and cause disease and mortality. Any salmon passing downstream could go from 22°C to 10°C almost instantly. Conversely, any upstream adult migrant may pass from 10°C to 22°C as it swims past the Clearwater River. Every hatchery manual and fish handling procedure emphasizes the thermal shock sensitivity of fish. Slow acclamation to temperature change is standard procedure. It is unclear whether the benefits of cooling some parts of the lower Snake River via Dworshak releases provides a net benefit due to potentially conflicting physiological needs for cool water and stable temperatures. We know of no mortality studies that expose fish to these contrasting environments and follow their survival rates compared to fish that are not exposed to such extreme spatial and temporal variation in temperature. The concept that dumping large amounts of cold water into warm water provides a net benefit to salmon is less clear than our ability to calculate the new temperature in the mixing zone. Of potentially greater issue may be the unproven assumption that more biological good than harm is created. Or, there may be benefits downstream and disbenefits upstream. We contend that this may need investigation. We know of no in-river data that currently address this hypothesis. We are aware of data that show thermal shock can harm or kill fish.

6.3 Review of the Biological Behavior of Salmon

Adult salmon do not migrate in mono-thermal environments. We know that spring chinook and some stocks of steelhead complete their migrations by July 1 in the mainstem. At this time of high flows, the rivers are cool (less than 20°C) and mostly unstratified. However, they are warming during the transition from spring to summer. These stocks are generally not exposed to thermal fluctuations or high temperatures in the mainstem. Fall chinook migrate later, in July to December, and are thus potentially exposed to some thermal risk and sudden variations. The question is, how many fish and how much risk?

Juvenile fall chinook disperse to the ocean over a longer migration period than spring chinook and in warmer water from July to December. Depending on the year, much of this migration period may not be exposed to temperatures above 20°C. However, juveniles that do migrate in drought years may be exposed to limited periods of temperatures greater than 20°C. Exposure may be limited in that the slow river movement (velocity) sets up the greatest potential for stratification (heterogeneity) in this period (see model discussion of Froude numbers). Adults and juveniles salmonids are known to sense and move to thermal preferenda, i.e., cooler water that may be available in the deeper sections of reservoirs during the day and shallow sections of reservoirs that may cool rapidly at night or in tributaries and springs. Shallows will tend to cool more than the middle of the river because the surface to volume is high allowing more heat to escape at night. There are documented vertical, horizontal and diurnal variations in temperature especially during the lowest flow and warmest months. A heterogeneous thermal environment presents opportunities for fish to move away from areas of thermal stress and risk, which they can and will do. For example, radio tagged adult salmon and steelhead often stage for hours or even days in cooler tributaries of the mainstem (cf. AFEP, 2001) before continuing migration up the Snake or Columbia Rivers.

6.4 Two Potential Thermal Problems for Salmon and Their Resolution

There are observed cases of two types of thermal stress during mainstem migration, one to adults and one to juveniles. Adults are sometimes delayed at the entrance to ladders in the Snake River. Because these ladders are gravity fed by surface waters (AFEP, 2002), the temperatures in the ladders may be considerably higher than in the deeper sections of the thalweg where adults are known to migrate. Thus, modifications to ladder water supplies may be appropriate mitigation to minimize, if not avoid, thermal exposure. Adults are also sometimes delayed from entering the Snake because of the differential between the Columbia and the Snake. This may be the uncommon result of differential runoff conditions between the two basins wherein high snowpack in the Columbia may be matched by low runoff in the Snake. In either event, removal of the lower Snake reservoirs does little to resolve the problem as evidenced by data or the EPA model. The solution in such unforgiving years of drought is transportation of juvenile fish as soon as captured in the Juvenile Bypass System (JBS) facilities.

Exposure of juveniles to unwanted thermal stress may occur also at or near the dams. JBSs are likewise supplied by surface waters. The low flows (due to screened dewatering) and extended periods of time juveniles spend in the JBSs may expose them to excessive time periods of thermal stress in the JBSs. This has been documented at places like McNary Dam. Juveniles were shown to average more than 16 hours to pass less than 100 yards from the upstream face to the downstream face of a dam and some fish took up to four days (AFEP, 2002) . The answer to this problem may lie in both better water supplies and hydraulics in the JBSs or more rapid passage across the dams. There is juvenile survival data (Harza, 2001) that suggest that the best strategy to maximize juvenile survival, especially in drought years, is not to pass any fish from a JBS back to the river. All collected fish should be transported, thus preventing unwanted lengthy exposure to high temperatures in the river. Transportation at the first collection point also minimizes multiple passes through the JBSs that are known to add mortality to the population (Harza, 2001).

One other potential source of juvenile thermal mortality is entrapment in the lower Snake reservoirs. In drought years, passage of fall chinook juveniles across Lower Granite Dam was observed to be very low (Connors, 1995). Flows may be as low as 15,000 cfs resulting in only one or two turbine units operating. Such low flows across the dams create low downstream velocities for fish. It is this downstream flow that cues fish to find their way out of the reservoir and through the dam. One possible means to improve this situation may be to use pulsed flows and partial drawdowns to enhance fish guidance efficiency into the JBS at Lower Granite Dam and into barges for rapid transport to the estuary. Removal of the dams would do little to improve temperature and prolong exposure in the warmer Snake River. Transportation would help alleviate this situation in low flow years.

Section 7 - Review of Alternative Models that Might be Applied to the Issue

7.1 General

Battelle Pacific Northwest National Research Lab has been modeling temperature conditions in the Lower Snake River for the U.S. Army Corps of Engineers for the past 5 years (cf. Richmond and Perkins, 1999, Perkins and Richmond, 2000, and personal communication, Marshall Richmond, 2002). Battelle provided copies of reports including those cited in the Reference Section for our review. The temperature modeling is part of a more comprehensive study to characterize the impacts of elevated temperatures and dissolved gas that may be affecting salmon survival in the reaches occupied by the four Lower Snake River dams and four lower Columbia River dams.

The primary tool used by Battelle to model temperature was a model called MASS1 or Modular Aquatic Simulation System 1 (Richmond 2000, Appendix B). Like the EPA 1-D Heat Budget Model, the MASS1 model compares the thermal behavior of the river in its current (with dams) condition versus a simulation of thermal behavior without dams. This model is a traditional one-dimensional heat exchange model. It assumes the temperatures measured at one point (scroll case, tailrace, forebay) represent the average condition throughout a reach of river; reaches are generally about 40 to 50 miles; this is about the distance between each dam (cf. Figure 2.2, Perkins and Richmond, 2000). Tributary inputs were from data, or assumed to be constant. Flow and temperature data from tributaries appeared to be spotty and assumptions were made about those missing data (p. 6). The key inputs to the model include upstream temperatures at starting points that are provided by data or assumption.

Battelle provides equations that show how they computed the heat exchange in each reach (Appendix B, Perkins and Richmond, 2000). Although they used meteorological data, it is unclear what percent of the solar radiation data were obtained by direct measurement versus computational estimates using cloud cover. Meteorological data are restricted to four stations: Lewiston, Idaho, Pasco, Washington, The Dalles, Oregon, and Portland, Oregon.

A constant inflow temperature of 14°C was the specified inflow temperature for tributaries that did not have data. Temperature was simulated for two seasons: 1996 and 1997. No parameters for air/water heat exchange were adjusted. Consequently, the simulations made were for verification; no calibration was performed.

Battelle developed the hydraulic component module to characterize the surface and volumetric conditions of these rivers at both natural river levels and at impoundment conditions by creating cross sections from a bathymetric simulation derived from navigation maps. Data density was variable and enabled simulated cross-sections every quarter- to half-mile. Despite these efforts, corrections to discharge rates (increases and decreases) were needed to achieve reasonable forebay elevations that approached the observed data set.

The authors provide the following potential causes of the hydraulic errors:

- The model may not account for all inflows to the pool upstream of the project;
- Posted project discharge may differ from the actual flow and may not account or other miscellaneous flows;
- Stage data are instantaneous, but flow data are an average over the last hour;
- Measured stages and flows may have biases;
- The available bathymetry may not accurately represent the available reservoir storage

Thus a correction factor, which supplied more or less flow, was applied in each reach in order to more closely approximate dam forebay elevation observations.

7.2 Model Results

The results of the modeling show general agreement between the simulation and the actual data. The model predicts daily temperatures within 1-1.5°C of the observed temperatures. This is similar to the EPA model in its precision. However, unlike the EPA Model, the Battelle Model simulates hourly time-steps, not daily ones. As a result, the Battelle model estimates excursions above 20°C on a finer scale than 24 hours.

Results of the Battelle simulations derive different consequences of reservoir removal that are nearly the opposite conclusions of EPA. When reservoirs are removed, the peak readings of temperature violations above the 20°C standard are actually higher without dams than they are with dams. The total time periods of violations of the with- and without-reservoir scenarios are quite similar. Although even here, the without-reservoir condition shows a slightly greater period of non-compliance than the current system with dams.

One area of agreement between the two models is that the timing of warming and cooling are both extended when dams are in place. Essentially, the thermal inertia of larger volumes (reservoirs) delays heating in the spring and delays cooling in the fall. Battelle concludes that, due to errors in the data and inaccuracies of the model, there is essentially no difference in the thermal regime of the lower Snake River with or without the reservoirs in place except for the time shift.

7.3 Comments on the Battelle Model and Results

Like the EPA Model, the Battelle model is one-dimensional and relies on historic (existing) data sets for temperature and meteorological data sets. As such, both models may be inadequate to address thermal impacts to salmon in detail because the system is a heterogeneous environment and these are 1-D models. Unlike the EPA model, Battelle uses quarter-hourly to hourly temperature data and as such provides a more continuous and dynamic picture of variation in the rivers temperatures. The result is there are higher daily peak temperatures in the unimpounded simulation. This is expected from a smaller body of water responding to diurnal heating and cooling cycles subject to summer solar conditions. Additionally, there is some seasonal thermal inertia whereby the reservoirs take longer to warm in the spring and are later to cool in the fall than the unimpounded river.

We encountered similar patterns in the lower Madison River and its controlling storage pool, Ennis Lake (GEI, 2002). Here the lake tends to buffer incoming temperatures and stabilize the discharge temperature and can work for or against managing lower river temperatures. At times, diurnal peaks of incoming river water are warmer than the reservoir and the outflows are cooler. However, late in the season, the reservoir gradually heats and outflows may be warmer than inflows. We have successfully utilized pulsing to counteract daytime heating in downstream reaches by increasing the volume of the river by timing pulses to arrive in the heat of the day. We are unaware of any type of pulse operations or seasonal volumetric adjustments that have even been considered for managing temperature in the Columbia system. The current tools would be unable to assess such potentials and for this reason suggest rationale for alternative data sets that may be of value discussed in Section 8.

Section 8 - Review of Improved Data that Might be Applied to the Issue

8.1 Is there a Rationale for More or Better Data Collection?

In their initial approach to this modeling effort, EPA described it as a preliminary effort to determine whether more detailed models might be needed (EPA, 1999). In our review of the initial model (Harza, 1999) we commented that the database was extremely weak and would lead to poor simulation or a large degree of error in the thermal output. It is also unclear how a model framework with 1-D daily time-steps could be used for any type of mitigation planning or validation other than making a dam removal decision. It is clear that the river does at times exceed the current standard of 20°C. Whether parts or all of the system would continue to exceed that standard with dams removed and to what extent cannot be ascertained with any degree of certainty with the EPA 1-D Model due to uncertainty caused by the data set. In other modeling efforts (Battelle, 2000) different conclusions add further concern to conclusions and results of the EPA simulation. What is needed at this point is a decision about whether temperature is significant enough of an issue to: 1) more globally characterize the problem or parts of the problem in terms of sources and potential mitigation solutions and 2) if so, establish what types of tools would be needed to characterize and prioritize solutions.

Further, integration of the biological issues into the solution and standards would seem relevant, as fish do not use models; they react to a complex and dynamic multidimensional environment. Because temperature mitigation could be costly to implement, it will be important to integrate priorities and cost-benefits into the effort. Once that type of planning effort is complete, then it would make more sense to invest in improved data collection and more useful simulation or predictive tools. Under the assumption that this might take place in the future and better data might be needed, the following provides a broad list of potentially valuable data that would enable greater precision in characterizing and resolving thermal issues.

8.2 Defining Data Needs

A suitable data collection program is the most essential step in any analytical effort. It should guard against redundancy, but ensure that no critical information is overlooked that would compromise the goals. It requires input from many sources. Although capital-intensive, it saves money in the end by enabling more reliable and flexible decisions. Instrumentation must be designed to deliver the level of accuracy required. It must be coordinated to assure that all of the necessary data are collected simultaneously and for a sufficient duration to achieve the overall goals. In the case of the lower Snake and Columbia rivers, several key questions need to be answered to determine an appropriate course of action:

- What are the actual thermal effects of each reservoir individually?
- What controls are available to counteract adverse thermal effects that are detected?
- What available controls could be effective?
- What constraints could affect controls?
- What are the upstream and tributary contributions of heat load to the lower river?
- What controls and constraints exist upstream?
- How do we empirically simulate and validate the results of mitigative actions?

8.3 Data Collection Categories

Several types of data need to be collected contemporaneously. Empirical observations may be nearly as valuable as more accurate modeling. The groups below organize the types of data that would be needed to accurately assess and analyze the thermal and hydraulic behavior of the reservoirs in the lower Snake and Columbia River systems.

8.4 Discharge and Project Operations:

This database would consist of an assemblage of information on how each of the plants in the projects is typically operated. It would contain the specifications on total capacities for each dam, and how the plant is generally operated. It would display historic data on typical operating levels at various times of the year.

- Pool Elevation
- Tailwater Elevation
- Turbine Discharge Patterns and Quantities
- Spill Operations
- Lock Operations
- Total Discharge

8.5 Project Operational Characteristics:

Project operational characteristics data would provide additional information on how each project is operated. Information included here would characterize whether or not the particular hydraulic structure has low-level outlet structures, selective withdrawal capabilities, and other systems that might be used to alter discharge temperature.

- Inlet and outlet works characteristics

- Hydraulic capacities
- Storage and release operations.

8.6 Bathymetry (taken at a range of flow rates and pool elevations)

Bathymetric data are important to characterize and quantify the flow characteristics, stratification potential, and velocity profiles within a particular reservoir. Although much of this and other information listed here may already exist, it should be organized and reviewed for completeness, accuracy, and quality, and any shortcomings addressed and augmented so that the information can be incorporated into more advanced hydraulic simulation routines.

- Cross Sectional Area
- Depth
- Length
- Reservoir Surface Area/Volume Rating Curves
- Channel Slope
- Channel Roughness

8.7 Water Temperature Profiles (taken at a range of flow rates and pool elevations)

Water temperature profiles are needed to: 1) gage stratification potential, 2) to ground truth and calibrate simulation models, 3) to verify densimetric Froude number calculations, and to 4) assist in hydraulic model design. Continuous temperature profiles could be measured using stationary buoys tethered to an anchor cable along which a number of temperature probes at various depths would yield a continuous three-dimensional temperature map of the reservoir being monitored.

- Vertical Temperature Profiles
- Lateral Temperature Profiles
- Longitudinal Temperature Profiles

8.8 Water Velocity Profiles (taken at a wide range of flow rates and pool elevations)

Doppler sonar technology is available to record three-dimensional velocity profiles. This technology would be useful to characterize current profiles and to generate flow velocity vector maps to assist in formulating hydraulic characteristics for large, deep reservoirs where stratification potential is strong and where it is necessary to characterize flow regimes to calibrate two- and three-dimensional hydraulics models.

- Vertical Reservoir Velocity Profiles
- Lateral Reservoir Velocity Profiles
- Longitudinal Reservoir Velocity Profiles
- Densimetric Froude number as function of local volume and flow

8.9 Tributary Data (average hourly data, all tributaries)

The flow and temperature data for tributaries are necessary to confirm the accuracy of synthesized data sets (if used), and to provide valid input data for modeling reaches of the river where significant tributary influxes occur. Temperature data can consist of simple self-contained temperature recording probes. Flow data can be gathered by the continuous electronic monitoring of stage (depth) that then can be correlated to a rating curve that yields discharge as a function of stage for each tributary.

- Tributary discharge and temperature at the confluence to the mainstem
- Other pertinent water quality data

8.10 Meteorology (average hourly data)

Local and precise meteorological data are crucial to simulating energy exchange rates at the air/water interface. Hourly data for 2 years throughout the period of interest, March-November would be minimum. The instruments should undergo systematic annual calibration traceable to NIST standards to ensure measurement precision. Modern meteorological stations are sophisticated, self-contained, solar and battery powered devices that can be equipped with telephone modems so they can be remotely managed, programmed, and interrogated. The suite of sensors should include: 1) evaporation pan data, 2) precision sensors designed to monitor the full spectrum of electromagnetic radiation, 3) wind speed and direction, 4) relative humidity and air temperature, 5) precipitation rate, 6) atmospheric pressure, and 7) local water quality variables of interest. The stations should be placed at regular intervals along the river to be analyzed (30 miles or less apart) so that a continuous representative suite of data are available to characterize local meteorological conditions. The distance between each station creates a simulation gradient between stations that meets at the halfway point.

- Air Temperature
- Relative Humidity
- Barometric Pressure
- Wind Speed
- Wind Direction
- Short Wave Solar Radiation

- Long Wave Solar and Atmospheric Radiation
- Interval Precipitation Rate
- Evaporation Pan Level
- Evaporation Pan Temperature
- Local River Temperature
- Local River Stage (Discharge)
- (Water quality, e.g. dissolved oxygen, conductivity, turbidity, TDG, pH, etc.)

8.11 Archiving of other Meteorological Data Sources:

In addition to local data collected at the project reaches, other local sources, such as weather forecast data, local airport data, AgriMet Station data, and others, should be captured and archived for comparison to data taken near the sites to correlate against direct measurements. These data, with proper conditioning and validated by local measurements, could legitimately serve to augment the data collected near the modeled reach. Such an approach would allow assessing data collected by other agencies for accuracy. Such an approach would enable these data to be selectively used if their accuracy proved to be reliable. Over the long term, more distant but permanent USGS weather stations could serve as the primary input data for the modeling effort after their calibration to local conditions was established.

Section 9 – Conclusions and Recommendations

9.1 Conclusions

Our conclusions about the actual constructs of EPA's 1-D Heat Budget Model are summarized as follows:

- The 1-D heat budget model is used to predict daily average water temperature. The predicted water temperature is not a real-time (instantaneous) temperature. The water quality standards in Oregon and Washington are written in terms of instantaneous temperature. Therefore, the results cannot be compared directly to the water quality standards for temperature.

- The predicted water temperature is an average across the width and depth of the river. The average water temperature does not consider the lateral, and vertical variations. Important spatial dimensions of the ecosystem are the longitudinal, lateral and vertical habitat below the river channel. The impoundment causes significant changes to the thermal regimes in all three dimensions, which the 1-D model cannot address.

- Within a water body the degree of heating is a direct function of the ratio of the surface area to the volume of the water. Depending upon the change in surface area, depth, and volume, the impoundment does not necessarily imply that the water temperature would increase as compared to the unimpounded condition.

- The impoundments in the Snake River increases the surface area slightly (71 to 135 percent). However, the depth increases considerably, between 310 and 504 percent, and volume increases even more, between 711 and 1,037 percent.

- For the Columbia River, the change due to the impoundment is not as sizable as the one shown for the Snake River. The surface area only increases between 6 and 118 percent. Whereas, the depth increases between 5 and 471 percent and volume increases between 64 and 631 percent.

- The following dams in the Columbia River impute volume change more than 150 percent above natural river: Chief Joseph, McNary, John Day, and Bonneville. The following dams in the Columbia River impute volume change less than 150 percent: Wells, Rocky Reach, Rock Island, Wanapum, Priest Rapid, and The Dalles.

- Stratification is highly variable among and even within sections of reservoirs. This has a significant implication of highly variable thermal behavior and is unrealistically treated as homogeneous by the EPA model. Such treatment compounds data error.

- Earlier field studies concluded that both Lake FDR on the Columbia River and Brownlee Reservoir on the Snake River cool river water temperature during spring and summer deep water releases. Although not modeled, acknowledgement of this situation offers greater range of potential solutions than removal of lower river dams and may deserve investigation.

- The variation and uncertainty in meteorological data quality makes the task of quantifying data measurements bias and error a difficult one. The uncertainty in cloud cover, wind speed, and evaporate rate would simulate unreliable parameters for the system model. The choice of appropriate meteorological stations to provide the data for the Snake and Columbia river basins must consider the spatial and temporal variations due to local phenomenon. The constraint of a limited number of stations with complete data creates additional uncertainty and thus affects the parameters for computing the heat flux exchange at the air-water interface. Examination of EPA input data shows moderate to poor correlation (goodness of fit) with nearby AgriMet station data. These patterns suggest that one of the biggest problems with the EPA model is simply an inadequate data set to reliably and accurately predict water temperature throughout the system.

- Since the 1-D heat budget model attempts to predict small changes of a few degrees or less, the hydrological and meteorological data must be carefully constructed, i.e., have extensive geographic coverage with low measurement error and a more continuous temporal measurement battery close to the river. Of particular concern is the model's lack of corroboration of very critical variables that drive thermal behavior, such as longwave radiation. Errors in estimating the water mass or synthesizing meteorological data would lead to errors in determining the water temperature response. The 1-D heat budget model is more applicable to predict water temperature in a small cooling pond with regular mixing. It has limited application to a highly diverse system of reservoirs and free flowing reaches each with distinct multi-dimensional thermal behavior due to difference is elevation, bathymetry, depth and size.

- The EPA model is an oversimplification of the thermal behavior of the river. That there is a net benefit of dumping large amounts of cold hypolimnetic water out of the Clearwater (Dworshak) is an unproven assumption. The mouth of the Clearwater will create a rather steep thermal gradient that may create potential for thermal shock due to sharp temporal and or geographic gradients. A 1-D model is incapable of assessing this benefits or disbenefits of the practice.

9.2 Recommendations

- The frequencies of water temperature exceeding the benchmark of 20°C are presented in the EPA report. It should be noted that this benchmark temperature is a regulatory artifact that does not truly fit the physiological requirements of salmonids. The limits of fish's thermal tolerance are generally evaluated in a controlled laboratory environment where fish are unable to adjust to stress. In the environment of the Columbia, spatial heterogeneity is the rule, not the exception, for temperature and many other variables. Using a model that describes it as monothermic is an oversimplification that simply does not fit the environment or the fish in it. Therefore, any regulatory standard meant to protect aquatic life, like salmon, should have a sliding scale based on both exposure time as well as severity above a standard. Currently the standard and the model adjudge the frequency of exceeding 0.2°C as the same as the frequency of exceeding 2.0°C.

- If more precise thermal modeling is needed, it may be desirable to use several models including multidimensional ones due to significant variation within and among reservoirs.

- A great deal more would be accomplished with collection of high quality data at limited reaches of the rivers than looking for mathematical functions to cover up bad data.

- Mitigation should also address the upper Snake River including Brownlee Reservoir. Dam removal will not cool already warmed water. The most cost effective mitigation for juveniles is probably related to improved JBS systems and transportation programs, especially in low flow, droughty years. Improvements to ladders water supplies as well as pulsed flows are other techniques that might lower mortalities at the dams associated with thermal stress.

- To assume thermal conditions are the only cause of mortality is a shortsighted assumption. Warm water can be accompanied by low dissolved oxygen and more active predators, especially exotics with warm water preferences.

- Dumping large amounts of cold water into a warm river provides only benefits and no disbenefits is unproven and may need to be investigated. A one-dimensional model is incapable of addressing this question.

- A more integrated approach combining higher quality physical data along with biological data may prove more useful in assessing the magnitude of thermal impacts and solutions.

Section 10 – References

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